AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

AGARD REPORT 821

Virtual Manufacturing

(la Fabrication virtuelle)

Papers presented at the 85th Meeting of the AGARD Structures and Materials Panel, held in Aalborg, Denmark, 13-14 October 1997.

North Atlantic Treaty Organization
Organisation du Traité de l'Atlantique Nord

The Mission of AGARD*

According to its Charter, the mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

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— Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);

— Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;

— Improving the co-operation among member nations in aerospace research and development;

— Exchange of scientific and technical information;

— Providing assistance to member nations for the purpose of increasing their scientific and technical potential;

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* AGARD merged with the Defence Research Group of NATO (DRG) on 1 January 1998 to form the Research and Technology Organization (RTO) of NATO. However, both AGARD and DRG will continue to issue publications under their own names in respect of work performed in 1997.

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Virtual Manufacturing

(AGARD-R-821)

Executive Summary

Virtual Manufacturing is an integrated, synthetic manufacturing environment exercised to enhance all levels of decision and control. This process uses product, process and resource models to evaluate the producibility and affordability of new product concepts prior to commitment to the final product design. Design processes are captured in a single geometric database and integrated with the planned manufacturing processes resulting in a simulation of the manufacturing environment. The critical questions of manufacturing cycle time, people resource requirements and physical resource requirements for various scenarios are quantified by simulation. Thus, Virtual Manufacturing is a tool to achieve more affordable aircraft designs, reduced cycle times and improved quality.

A very successful Workshop on Virtual Manufacturing was held by the former AGARD Structures and Materials Panel on 13 and 14 October 1997. A total of 14 papers was presented on a wide range of subjects related to Virtual Manufacturing. As a key theme observed during the Workshop was the commitment to solid models and the use of virtual mock-ups by Aerospace companies. This technology has demonstrated tremendous benefits related to communication between product development teams and first time fit for quality. An emerging use of solid models is virtual manufacturing where these same solid models are used to develop and validate manufacturing concepts prior to fabrication to hardware. A number of papers were presented that highlighted this aspect of virtual manufacturing. Several papers were also presented highlighting the commitment of the JSF program (Joint Strike Fighter) to Virtual Manufacturing. Total savings of 3 to 6% of life cycle costs are expected. A number of papers were also presented that addressed related issues such as simulation of part fabrication processes, cost relationships and virtual reality training. These papers pointed out the breadth of the subject of virtual manufacturing and how it related to many aspects of product development.

Another common theme from the workshop was that to make a real impact on costs, lead times and quality you need the added ingredients of people and processes. Processes need to be clearly defined within the organization since past experience has shown that placing technology on top of a company with poor processes will have little impact. With regard to the people issues, Concurrent Engineering philosophy states that the ideal scenario is multi-discipline teams working together to concurrently engineer the product. Concurrently, the structures designer designs the airframe, the systems designer routes pipes and wires through the structure, and manufacturing provides early producibility inputs to ensure an affordable product. Technology can be seen as the enabler in this case because the tools allow multi-user concurrent access to the data. If the team is not physically located together, then technology can also help out by using high speed communications to bring the team together using video and audio.

In the Round Table discussion at the end of the Workshop, it was suggested that a follow-on activity be conducted in approximately two years.

Atelier sur la fabrication virtuelle
(AGARD-R-821)

Synthèse

La fabrication virtuelle est un environnement de production synthétique intégré qui permet des améliorations à tous les niveaux de décision et de contrôle. Ce processus utilise des modèles de produits, de procédés et de moyens pour évaluer la productibilité et le coût de possession acceptable des nouveaux concepts produit, avant de procéder au lancement du produit final.

Les différentes étapes de la conception sont saisies dans une base de données géométrique unique, puis intégrées aux processus de fabrication prévus, entraînant une simulation de l'environnement de fabrication. Les considérations critiques des temps de cycle de fabrication et des ressources humaines et matérielles à prévoir par rapport à différents scénarios sont quantifiées par simulation.

Ainsi, la fabrication virtuelle est un outil qui permet de réaliser des études d'aéronefs à coût de possession plus acceptable avec des cycles de conception réduits et une meilleure qualité.

Un atelier très réussi sur la fabrication virtuelle a été organisé par l'ancien Panel AGARD des Structures et Matériaux (SMP) les 13 et 14 octobre 1997. Quatorze communications couvrant un large éventail de sujets se rapportant à la fabrication virtuelle ont été présentées. L'un des thèmes clés de l'atelier a été la préférence exprimée par les sociétés aérospatiales pour les modèles solides et les maquettes virtuelles. Cette technologie offre d'énormes avantages en ce qui concerne les échanges entre les équipes de développement des produits, et en outre, la justesse du prototype qui en résulte permet une nette amélioration de la qualité. L'utilisation toute récente de modèles solides est un exemple de fabrication virtuelle dans la mesure où ces mêmes modèles solides sont utilisés pour le développement et la validation de concepts de fabrication avant le lancement de la production en série. Un certain nombre de communications ont été présentées sur cet aspect de la fabrication virtuelle. D'autres présentations encore ont mis l'accent sur l'option prise par le programme JSF (Joint Strike Fighter) en faveur de la fabrication virtuelle. Une économie globale de 3% à 6% sur les coûts de possession est prévue. Enfin, quelques communications ont été présentées sur des aspects connexes tels que la simulation des procédés de fabrication des pièces, l'interaction des coûts et la formation en réalité virtuelle. Ces communications ont souligné l'ampleur du sujet de la fabrication virtuelle et ses liens avec divers aspects du développement de produits.

Un autre thème évoqué à plusieurs reprises lors de l'atelier a été l'importance du facteur humain et des processus dans l'optimisation des coûts, des délais et de la qualité. Il y a lieu de définir très clairement les processus au sein de l'organisation, car l'expérience démontre que le simple fait d'adopter des technologies sans disposer de processus adaptés n'a que peu d'impact sur les performances d'une entreprise. En ce qui concerne les questions du personnel, la philosophie de la conception technique simultanée stipule que le scénario idéal est celui où des équipes pluridisciplinaires travaillent en collaboration sur la conception simultanée d'un produit donnée. Selon cette approche, le concepteur structures réalise l'étude de la cellule en même temps que le concepteur systèmes élabore le plan d'acheminement des gaines et des câbles dans la structure et que la cellule production fournit les données sur la productibilité, susceptibles d'assurer l'acceptabilité financière du produit final. La technologie peut être considérée ici comme un facilitateur, car les outils donnent au multi-utilisateur l'accès simultané aux données. Dans le cas d'une équipe dont les membres se trouvent sur des sites différents, des liaisons vidéo et audio à haute vitesse peuvent être établies pour assurer la coordination du groupe.

Il a été proposé, lors de la table ronde qui a clôturé l'atelier, qu'une activité complémentaire soit organisé dans deux ans environ.

Contents

† Paper not available at time of printing.

Preface

Virtual Manufacturing is an integrated, synthetic manufacturing environment exercised to enhance all levels of decision and control. This process uses product, process and resource models to evaluate the producibility and affordability of new product concepts prior to commitment to the final product design. Design processes are captured in a single geometric database and integrated with the planned manufacturing processes resulting in a simulation of the manufacturing environment. The critical questions of manufacturing cycle time, people resource requirements and physical resource requirements for various scenarios are quantified by simulation. Thus, Virtual Manufacturing is a tool to achieve more affordable aircraft designs, reduced cycle times and improved quantity.

The objective of the Workshop was to examine the state-of-the-art in Virtual Manufacturing to quantify the cost benefits that can be realized using this type of technology and to identify where the community needs to go to realize these benefits.

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TECHNICAL EVALUATION REPORT

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AGARD

85th Meeting of the Structures and Materials Panel

Workshop 1

Virtual Manufacturing

(13-14 October 1997)

Location: Kongres & Kultur Center
Aalborg, Denmark

Chairmen: Mr. John M. Coyle, Boeing Information, Space, & Defense Systems, USA
Dr. Donald B. Paul, United States Air Force, USA

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1. INTRODUCTION

Virtual Manufacturing offers the potential to significantly lower non-recurring product development costs, recurring production costs, and post delivered product support costs. This objective is accomplished through the innovative integration of design and production solid models with advanced simulation technology. The use of Virtual Manufacturing by multi-functional Integrated Product Teams, enables these teams to dramatically improve the quality of their products through accurate cost, schedule, and risk analyses prior to commitment to product manufacture. Virtual Manufacturing tools enable team members to inexpensively address "what if questions" prior to production implementation and obtain early collaborative team "buy-in" for production changes. The RTO AGARD 85th meeting in Aalborg, Denmark provided a workshop forum to review industry, academia, and military customer strategies, implementation methodologies, and deployment status of Virtual Manufacturing.

2. THEME OF THE WORKSHOP

Virtual Manufacturing is an integrated synthetic manufacturing environment exercised to enhance all levels of decision and control. This process uses product, process, and resource models to evaluate the producibility and affordability of new product and process concepts prior to final commitment. Design processes and parameters are captured in a single geometric database and integrated with the planned manufacturing processes resulting in a simulation of the manufacturing environment. The critical questions of manufacturing cycle time, people resource requirements, and physical resource requirements for various scenarios are quantified and proven with simulation. Thus, Virtual Manufacturing tools enable more affordable aircraft designs that operate in new modes, characterized by reduced design and manufacturing cycles and lower risk.

3. PURPOSE AND SCOPE

The purpose of the workshop was to exchange information on a broad range of research, development, and deployment progress on the topic of Virtual Manufacturing, as presented by representatives from the NATO countries.

The scope of the Virtual Manufacturing workshop included the strategies, tactical plans, and implementation progress on specific air vehicle programs. Topics and discussions ranged from the use of simulation tools during the earliest stages (conceptual design) of product development, to strategic applications of this specialized technology on the production shop floor. Categories of Virtual Manufacturing topics presented at the workshop included: the methodologies and implementations within the aerospace industry, the expectations and perspective of the U.S. military on Virtual Manufacturing, and supportive research in

the academic field throughout Europe and the United States.

The information was conveyed to the forty-five (45) participants during the two day workshop through fourteen (14) pre-written white papers, fourteen (14) formal presentations, video tape presentations, question and answer sessions, and a round table discussion with AGARD panel members, technical presenters, workshop recorders, and workshop attendees.

4. WORKSHOP OVERVIEW

The importance of Virtual Manufacturing in product development throughout aerospace was evident by the extent of participation and the current breadth of its implementation. Virtual Manufacturing papers were presented by the following participant groups:

- Aerospatiale, France
- The Boeing Company, United States
- British Aerospace, United Kingdom
- Catholic University of Leuven, Belgium
- Daimler Benz Aerospace, Germany
- Dassault Aviation, France
- Hughes Aircraft, United States
- Joint Strike Fighter Program Office, United States
- Lockheed Martin, United States
- Prosolvia, Sweden
- Short Brothers, United Kingdom
- University of Greenwich, United Kingdom
- United States Air Force, WL/MTIM,

Data received extensive dissemination due to the breadth of NATO representation at the workshop. Countries participating at the workshop included: Belgium, Denmark, France, Germany, Greece, Italy, Norway, Spain, Sweden, Turkey, United Kingdom, and the United States.

The workshop was successful from a number of perspectives. First, the exchange of information provided substantiation that most aerospace firms are committed to the deployment of solid modeling and Virtual Manufacturing and are placing importance of this key technology in their product development process. Secondly, information concerning their approach to implementation and lessons learned can be used to reduce risks to those planning to further expand the use of this capability. Thirdly, the workshop provided an information forum that would have been very costly for the participating groups to have individually benchmarked each of the presenter's factories. Lastly, the white papers and presentations conveyed trends in the industry and gave specific information that will aid in determining where additional research is needed and where it may be applied.

Differing levels of experience were highlighted during the workshop. This information can be to expand the use of Virtual Manufacturing by focusing investigations with participant firms who may have experience to share and build upon. Overall, the workshop was very beneficial to the participants, and successfully met the objectives of the 85th meeting of the Structures and Materials Panel, Workshop 1.

5. CONCURRENT ENGINEERING

Both the white papers and workshop presentations described a consistent theme throughout aerospace. All have recognized the costly aspects of new product development and as a result, have established objectives to significantly improve the processes of product development, manufacture, and customer support. Virtual Manufacturing was consistently identified as a critical tool, used in conjunction with the Concurrent Engineering organizational philosophy, to improve the product development process and the resultant product and processes used to produce it. The definition of Concurrent Engineering, as described by a workshop presenter, is as follows:

"a systematic approach to creating a product design, that considers in parallel all elements of the product life cycle from conception of the design to disposal of the product, and in so doing, defines the product, its manufacturing processes, and all other required life cycle processes such as logistics support. Using multi-functional teams, it ensures that design, manufacturing, procurement, and marketing all work together in parallel, from concept through to the final launch of the product onto the marketplace."

Concurrent Engineering consists of the use of Integrated Product Teams, lean manufacturing techniques, and the use of the latest CAD/CAM technologies and tools. The multi-disciplinary aspect of the Integrated Product Team assures that the teams are staffed with design, manufacturing, procurement, marketing, etc., and that all work in parallel to assure accuracy, completeness, and producibility of the product definition. Product life-cycle costs are established at the earliest design stage and Virtual Manufacturing tools play a critical role in the Integrated Product Team's ability to dramatically reduce these costs.

Papers supported the premise that Concurrent Engineering is the organizational foundation for product development for future generation aerospace products. Virtual Manufacturing was identified as a key enabler to achieve the ambitious affordability objectives associated with the implementation of Concurrent Engineering. This position is supported by the Joint Strike Fighter Program Office. The Joint Strike Fighter presentation expressed strong support for early integration of design and manufacturing. "The approach taken to assure JSF affordability, supportability, and survivability is through the deployment of a threefold strategy: Lean Manufacturing, Manufacturing Tools and Methodologies, and Virtual Manufacturing and Assembly."

6. VIRTUAL MANUFACTURING

Concurrent Engineering enables companies to affect such business drivers as:

- improved time to market,
- improved product quality, reliability, and maintainability, and
- reduced cost of design development, production, and support.

Virtual Manufacturing tools can provide the ability to analyze product design and provide feedback on affordability objectives in the earliest stage of product development. A definition of Virtual Manufacturing provided from one white paper generally describes the workshop presenters' collective view on the subject.

"Virtual Manufacturing is an integrated set of tools and technologies which provide a highly accurate, near real time, three dimensional simulation environment to evaluate new or existing methods and processes; tool and fixture design/assembly sequences; facility layouts and material flow; ergonomic/human factors; and alternate production scenarios involving one or more products."

Virtual Manufacturing is sound in concept and currently available for use in product development throughout aerospace. Video presentations of existing work at Dassault on the Rafale Program, Lockheed Martin on the JSF Program, and Boeing on the JSF Program, clearly demonstrated the commitment to Virtual Manufacturing deployment and its powerful capabilities in the product development process. Additional presentations also demonstrated various levels of commitment and implementation. In general however, all presenters had a sophisticated understanding of the tool and its potential benefits. Daimler Benz presented the perspective of the power of the simulation tool in virtually every phase of product development from conceptual design, preliminary design, detailed design, manufacturing, and product support.

7. SOLID MODELS

A necessary supporting element required to exploit Virtual Manufacturing simulation capabilities is the commitment and development of "solids geometry" product definition. A consistent theme woven throughout the presentations by participant companies, who had previously implemented various levels of Virtual Manufacturing, identified the need for overall commitment and discipline of both the company leadership and the technical staff in the creation of product definition using solids geometry. The use of such systems as UNIGRAPHICS, CATIA, Applicon Bravo, CADD55, AutoCad, etc., were common graphics modelers identified by the presenters as necessary tools to develop the solids geometric data. Simulation software such as Quest, IGRIP/ERGO, Arena, Witness, VSA, etc. uses the solids data, or its derivatives, as the fundamental data source for simulation. Presenters indicated that companies intending to exploit the benefits of simulation, must make a commitment to:

- acquire the required levels of advanced CAD/CAM and simulation software and hardware tools,
- train the workforce on required modeling techniques and simulation applications, and
- manage the Integrated Product Teams effectively in the application of these tools throughout the Product Definition, manufacturing, and support phases.

Presenters also indicated that full three-dimensional solid models placed a strain on

older CAD/CAM and data management systems. They also pointed out the need for standardization such as ISO 10303-2-3 (Step AP 203). Standardization provides the basis for software development houses to provide industry with advanced simulation tools to support Virtual Manufacturing at a reasonable cost. Standardization also provides the foundation for driving cost down for CAD/CAM and simulation software to better equip industry in general. As the global economy expands, the role of partnerships, subcontractors, and other multi-company endeavors, availability of low cost compatible software is needed. The challenge to industry is the ability to integrate new solid model and Virtual Manufacturing tools with existing legacy software and hardware to support Concurrent Engineering objectives.

8. VIRTUAL MANUFACTURING APPLICATIONS

The presentations indicated that industry in general has various levels of deployment and are using or targeting Virtual Manufacturing use in a variety of applications. It can accurately simulate all levels of decision and control in a manufacturing enterprise. The following is a compilation of Virtual Manufacturing applications identified in the presentations.

Electronic Mockup

The initial step aerospace firms have taken in the deployment of Virtual Manufacturing has been the creation of the "electronic mock-up." Replacing hardware prototypes with computational prototypes, can greatly reduce product development times, manufacturing facility ramp-up times, and product development costs. Benefits of the electronic mockup include: reduced learning time on first article assembly due to dynamic visualization enabling improved training; reduced post design changes due to poor assembly and/or maintainability problems; and estimated work content and cycle time for both production of the air vehicle as well as its maintenance support in the field. The key advantages of the electronic mockup include:

- part-to-part fit verification,
- automated interference checking of parts, tools, etc.,
- avoidance of revisions to structural designs due to interference,
- determining optimum manufacturing flow and assembly sequences,
- determining maintenance accessibility,
- managing space allocation during design, and
- the ability to study assembly/component kinematics.

Design-To-Cost

Increasing pressures on new program startups have driven industry to aggressively pursue reduced time-to-market and overall weapon system life-cycle-cost objectives. Both time-to-market and life-cycle-cost are significantly impacted during the product development stages of conceptual, preliminary, and detail design. A key initiative to accomplish these objectives is through a disciplined design-

to-cost philosophy deployed by the Integrated Product Teams at the earliest stage of product development. Tools such as the Simulation Assessment Validation Environment (SAVE) program, under development by the Joint Strike Fighter Program, incorporates simulation tools to integrate planning, tolerancing, scheduling, assembly, factory, ergonomic, and feature-based costing. SAVE will implement a flexible open architecture allowing new tools to be easily plugged into the overall system. This architecture will enable different tools to be added to the network by developing CORBA wrappers for that tool to enable a SAVE compliant interface to the infrastructure. The primary objectives of this effort are:

- to improve design-to-cost data accuracy,
- optimize lead times,
- reduce design changes,
- reduce cost of quality,
- control process capability,
- reduce inventory turn time,
- and reduce fabrication and assembly inspection.

Key to this effort is the integration of simulation tools, hardware and software infrastructure, and feature-based cost models.

Factory Simulation

Virtual Manufacturing can provide insight into product flow and its critical path. Factory simulation software not only can predict key operational performance parameters, but can aid in low cost factory optimization analyses. It can provide the means of analyzing proposed changes and their resulting payoff prior to their physical implementation, thus reducing risk. The significant result is the startup of production much further down the learning curve than with conventional startups. Another key result is optimized overall cycle times.

Factory space can be "walked through" by virtual people ensuring that factory layouts account for human interface and ergonomic issues. Because Virtual Manufacturing is an off-line software based process, this can be efficiently accomplished without impact to ongoing operations. Key features identified through the use of factory simulation include:

- Numerical Control Program Checkout and Validation,
- Work Cell Layouts and Factory Flows,
- Optimized Product Flow and Assembly Sequences,
- Total Product Flow Cycle Time,
- Identification of Critical Path and Potential Bottlenecks, and
- Constraint Analyses.

Virtual Manufacturing enables Integrated Product Teams to thoroughly investigate proposed changes in products and processes, test the results, and quickly implement them with the least amount of disruption in the process. Key factory flow, can be evaluated upstream to significantly lower risk during initial production startup.

Discrete Process Simulation

Another powerful aspect of Virtual Manufacturing is the ability to exploit solid

geometric product definition in the analyses of Part-to-part fit, as well as detailed interactions of parts, tooling, portable equipment, fastener installation, and ergonomic effects on humans. In addition, simulation capabilities allow for non-physical analyses of numerical control programs and machine tool operations. Key applications identified in the workshop presentations included:

- Tooling and Equipment Interaction Evaluations,
- Machine Tool Development,
- Manual Process Optimization,
- Media/Program Try-Outs (First Part Try-Outs),
- Machine Tool Reach and Collision Avoidance Studies,
- Off-line Numerical Control Program Verification,
- Process Modeling For Optimizing Raw Material Transformation To Detail Parts,
- Human Factors and Man-Machine Interface Analyses, and
- Modeling of the casting process.

Work Instructions

Another powerful application of Virtual Manufacturing identified was the use of the solids geometry in conjunction with simulation tools to perform or supplement the use of manufacturing Work Instructions. Virtual Manufacturing can be used to visualize, understand and determine process plans resulting in more consistent, accurate, and error-free process planning. This same model can then be used on a recurring basis in the actual production process to provide the following dynamic functions:

- Complex Systems Installation,
- Animated Assembly Sequence and Training,
- Installation of Component Structure,
- Verification/Inspection Processes, and
- Paperless Shop Floor Graphics.

The paper presented by the Catholic University of Leuvin describes an approach to feature based computer aided process planning which utilizes a mixture of human interaction and automation to take advantage of the best of both areas.

Communications

The solid geometry product definition, coupled with simulation software capability provides a broad range of sophisticated communications capability. These communications can range from photo-realistic renderings of the product, to "fly-throughs" of internal structure of the air vehicle. These sophisticated applications can significantly enhance customer understanding of product offerings, as well as key functions of the subsystems, support, and maintenance. These communication capabilities can be effectively utilized by all levels of the technical staff, management, and groups such as marketing.

Future

Virtual Manufacturing is at a state where production applications are currently expanding throughout aerospace. Although software system development continues, there is ample room for further applications

using existing software products. It is expected that aerospace firms will continue expansion in the following areas:

- kinematics studies with moving parts and subassemblies,
- verification of product subcomponents and systems operations through kinematics studies, and
- realism increased through use of sound, touch, and other parameters.

However, as the industry becomes more mature in its application of Virtual Manufacturing, the need exists for more integrated CAD/CAM and simulation software to support this.

9. CONCLUSION

The workshop validated the collective view from the NATO aerospace industrialists, that Virtual Manufacturing plays a key role in modern air vehicle product development. Presentations demonstrated the varied levels of deployment currently throughout industry. However, it was observed that all firms are moving in the same general deployment direction with their Virtual Manufacturing applications.

There are immediate needs from the computer industry to support this growth with better, more sophisticated CAD/CAM software applications, data management systems, and data transfer technologies, especially to handle large solid models. However, it was felt that this deficiency in computer technology should not deter firms from an aggressive deployment strategy for Virtual Manufacturing. The dynamic state of the computer technology field is expected to keep track with the expansion of Virtual Manufacturing deployment.

Previous applications of Virtual Manufacturing have demonstrated its significant potential for reducing cost, cycle time, and quality throughout the product development process. However, for most firms, there remains significant opportunity to further expand its deployment and subsequently reach higher levels of performance. This is true not only from the perspective of product development costs, but also in the area of recurring production costs. The workshop validated the fact that Virtual Manufacturing is now an integral part of the product development process within aerospace worldwide and continues to have significant growth potential in furthering its applications.

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Use of Virtual Prototyping in Design and Manufacturing

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Introduction

In 1989 Shorts first looked at the potential of replacing physical wooden mock-ups with electronic solid model assemblies. They took existing drawings of the F100 wing and translated these into a solid mock-up. Although these early solid modellers were not user friendly , the resulting demonstrator was impressive and proved that large assemblies could be produced. This gave Shorts the confidence to embark on a small production contract - Trent Nacelle. This had 10 designers working concurrently generating structures, hydraulic and electrical systems all as solid models. Initially there was concern because the project planners who traditionally measure drawing output were getting very little drawings released during the first half of the program as the solid models and assemblies were being created. However, the drawing output increased dramatically near the end because of the fast production of assembly drawings giving a resulting overall reduction in leadtime of 20%. This result set the scene for the technology strategy on the Lear 45 when the decision was made to solid model the complete aircraft including all structures, hydraulic and electrical systems.

Concurrent Engineering Strategy on the Lear 45

The engineering strategy set on the Lear 45 was based around the three cornered approach of Process, People and Technology.-See Figure 1. You need to satisfy the needs of all three areas to gain success. This was a very ambitious strategy with major changes in culture required. In many companies the responsibility of who develops the CADCAM strategy is not clear. Engineering management do not have a good understanding of the technology and are more focussed on engineering tasks involved in projects. Similarily, specialist departments such as CADCAM are more technology focussed , without a detailed understanding of the engineering processes. To overcome this problem on the Lear45 an "Engineering Process Improvement Centre " was set up. - EPI Centre. This group had the responsibility for the use and integration of the technology on the program. Technology implementation is an integral part of the engineering process. Results are dependant on close liason between all parties, together with the resources and support where required..

The people aspect of concurrent engineering implemented on the Lear 45 was the integrated team approach with everyone on the team working towards the same common

Paper presented at the AGARD SMP Meeting on "Virtual Manufacturing", held in Aalborg, Denmark, 13-14 October 1997, and published in R-821.

goal.- see Figure 2. Using multi-functional teams it ensures that design, manufacturing , procurement and marketing all work together in parallel, from concept through to the final launch of the product onto the marketplace. As the majority of product costs are committed at the design stages of the product life cycle, it is rudimentary to ensure all downstream functions have their input to the design. As the teams are multifunctional in nature the organisational structure required is that of a project or matrix management. The traditional functional organisâtion has many disadvantages, some of which are as follows.

Functional systems rely heavily on systems and procedures.

Prevents good cross functional communication.

Slow to react to change.

As an individual , their importance is fulfilling the allocated role in the structure.

The system breeds specialist rather than rounded engineers.

Priorities are decided at departmental level, possibly without a clear corporate objective.

Functional activities are optimised, possibly to the detriment of the overall benefits of the project.

The sequential activities in a functional structure can cause a complete rerun of a portion of project activities when a problem is discovered.

To reduce the disadvantages inherent in the functional organisational structure a matrix management structure is used to provide focus on the project objectives. The major dissadvantage with the matrix structure is the complicated reporting relationships of the staff on the teams . This was a major cultural change for Shorts as it is with most companies who have been functionally organised for decades. Some of the problems were as follows:

- Individuals are seconded onto teams with a project manager (DBT Leader) as their superior. At the same time the individual has a link to their functional manager for "professional guidence". This multi-reporting relationship can be prone to conflict if the DBT leader and functional managers have different priorities.

- Individuals seconded onto the team should be empowered to make decisions as active members of the team. A major problem can exist if the individual is inexperienced and either not capable of making most of the decisions required by the team or the functional management vetos the decisions made by a team member. To further confuse

this new role the existing job descriptions were functional based and relevant for a role culture and not a team based culture.

- To resolve these problems, the changed roles and responsibilities for all the members of the organisation must be clearly understood together with the operating rules for the team. The extent to which an individual is empowered must be clear and accepted between the functional manager, individual in question and the DBT leader.

The Zone manager who supports the DBT is responsible for the electronic mock-up for that zone of the aircraft. He is also responsible and has control of the product structure tree for the zone. If a designer wants to add new parts, then the zone manager has to be notified as he has control over the master tree. As well as the basic technology of solid modelling , the importance of the product structure tree in managing the whole infrastructure of the mock-up must be understood.

Product Structure Tree.

Shorts work on a "Design as Built" philosophy i.e. the design is based on the jigged assemblies which will be used on the shop floor. Before the start of the design process a Pert structure is generated and this is basically a family tree of all the jigged assemblies that will be used. From this PERT structure , product structure trees are created for the scheming stage of the design process. As the schemes are frozen, detailed product structure trees are generated for each jigged assembly which show every detail part and piece of hardware which are required for that assembly and the sub-assemblies within it. These product structure trees are the basis of the whole design process within Shorts. The trees are created, modified and controlled by the Zone Manager using a Computervision product called Optegra Navigator. This is a windows based product which is easy to use with a minimum of training. Only the Zone managers have the authority to create or modify the trees which means the product structure is tightly controlled. Any major changes to the product structure also have to be approved by the relevant design/build team after consideration by all the parties involved. Figure 3 shows a typical design tree for a Learjet jigged assembly .

Each node on the tree represents an item in the assembly, with the drawing number, part description and instance number displayed on the node. The instance number is required to allow for situations where a particular item is used more than once in the product . Behind each node there is a 3D geometry file which can be either Cadds or Catia, as well as additional non-graphical information, known as attributes, for that part. Both the 3D geometry model and the attributes are stored in the engineering database which is controlled by the Optegra Vault software. The first instance of a part is modelled in aircraft coordinates i.e. in its correct position within the aircraft. Subsequent instances simply point to the geometry model of the first instance and apply an orientation matrix to

position the part correctly within the aircraft. The orientation matrix is held as an attribute within the tree. This means that if a part which has more than one instance changes, only one geometry model needs to be updated and controlled. The attributes associated with each item on the tree, and the sheet on which they are laid out, are totally customisable for each contract since the required information changes from one contract to another. Examples of typical attributes used are shown in Figure 4.

Workflow

Shorts learned alot from the Lear 45 contract. One thing there was general agreement on , was the need for some type of formal system to give better management visibility of the approval and release mechanism which was happening during the product design process. It was agreed that the best solution to this problem would be a Workflow system with electronic approval and release. This would enable managers to get accurate visiblity of the drawings released, the drawings which were currently being reviewed etc. Figure 5 illustrates the workflow process. At the end of the scheming phase of design the number of details in the assemblies are broken out ready for the detail design phase. At this stage the detail is given an official part number and a blank part created in the Engineering Data Management System. This phase is defined as the prework phase. -PW . The Lead Designer then assigns different details to the "Work to Lists" of individual designers.- Process 1 The individual designer then takes this part out and starts detailing.- (IW -In work status.) When the designer has completed his detailing he submits his drawing for review. The part is now at IR- In Review Status. The main reviewers within Shorts are Lead Designer, Stress, Weights and Manufacturing. All these areas have their own terminals for reviewing the drawing and electronically signing off. Reviewers receive a review task on their own work to list. Process 2. If one or more of the reviewers reject the drawing then the drawing goes back to "In Work" status with a message stating why the drawing was rejected. - Process 3. If there is unanimous approval of the drawing (process 4), then the drawing goes into RRL -Ready for Release phase. This phase is simply to let the reprographics department put the pack of information together for the final stage of release when the engineering drawing release note is completed and the status goes to RL. Shorts have found the major business benefits of the Workflow system to be as follows.

- The approval and release phase for drawings can be a large proportion of the total time taken for the design task. There are major productivity gains to be had by putting in place control mechanisms to ensure that the right tasks are done by the right people at the right time and in the right sequence. This means resources are maximised by ensuring that tasks which logically can be done in parallel happen that way rather than in series.

- The Workflow system gives management a single source of accurate information on the current status of every drawing within the design phase. In the past this information came from many sources and it was difficult to validate the true picture. The Workflow system ensures the consistancy and integrity of the data used for management information and decision.

Executive Information System

Another major lesson learned on the Lear 45 was the need to have some system to give visibility of the following information as the design is evolving.

Recurring Costs against Target Costs.

Roll up Weights against Target Weight.

Drawing Release against Schedule

The idea was to have a simple and easy to use interface on a PC which could be used by executives to get access to the latest information on these elements. A typical screen is shown in Figure 6. By clicking on a certain area of the aircraft, you get a traffic light system displayed for each of the elements. A red light signifies that there is a problem . An orange light signifies that the value is over but within 5% of the target. Green signifies that the values are fine. The information held on this database is taken from several sources. The attribute information held with the part geometry, the project planning system schedules, the Workflow system , the product structure tree definitions held in Optegra. The system allows the manager to drill down through the different levels of assemblies and find the source of the problem. i.e. you can get a traffic light display for a complete wing or a display for single rib within the wing. Similarily, you may get a red light for the total weight for a fuselage, but on further investigation at lower levels you may find that it is just a single frame that is overweight. With a knowledge of the total product structure tree and attribute information on costs and weights for each part , it is easy for the system to roll up the total values for any individual part or level of sub-assembly.

Access and Maintainability Problems.

During the manufacture of the Lear 45, major access problems were encountered in the systems area above the baggage bay. The existing electronic mock up had not identified any access problems in this area. In order to resolve the problem, additional access panels were cut out of the skin panels and some existing access panels had to be redesigned. This highlighted the limitations of the existing electronic mock-up processes and as a result, a

development project was initiated to research various approaches to removing these limitations. The main limitation with electronic mock-ups is the difficulty in simulating the human access and interaction required to evaluate assembly and maintenance. With this in mind, the project objectives were defined.

The project is a three year research project, part funded by local government and is a joint venture between Shorts and Queen's University, Belfast. It initially identified three approaches to the problem :-

a) Immersive Virtual Reality.

b) A Standard 3D CAD manakin

c) Fully functional manakin in a highly interactive 3D environment.

The results of the project will enable early design concepts, captured as 3D CAD models, to be analysed by assembly planners and product support personnel to identify areas of concern. Simulation of the build and maintenance tasks can then be performed, using these advanced CADCAM tools, and the optimum solution determined. Assembly planners will be able to run "what if " scenarios, changing the assembly sequence so as to determine the most efficient. These sequences can also be captured and used to train assembly fitters. Product support personnel will check that there is sufficient access for maintenance tasks and evaluate ease of performance of these tasks. Emphasis on tooling access and configuration will ensure the tasks are achievable.
In Shorts, expertise in solid modelling and product visualisation have already been gained through the Lear 45 and Global Express contracts. These projects have amassed several man years of expertise in the creation of virtual product definitions. The models are realistic and of high resolution. Interaction with the model, within normal CAD visualisation software, is restricted. In many cases mechanisms cannot be tested, such as hinges, slides and fixing interactions. Subassemblies should be moved in the same way as the assembly operator physically carries out the task; this cannot at present be attempted. These operations require event based software and user written code which is difficult to interface in CAD packages but is a built-in component of VR packages. Modelling the interactions of the user, assembly tools and parts will allow specialist tool design and realistic system tests. Virtual reality can provide various levels of interaction of the designer with the assembly. The model can be viewed in three dimensions, parts moved in mechanism based directions, and realism of interaction is increased through use of sound, touch and other parameters.

For the system to work efficiently and provide effective support for integrated product development teams, the system has to be integrated into Shorts existing information systems. This would include

♦ Integration With Shorts Current EDM System. (CV Optegra).

♦ Being able to select parts and assemblies from Product Structure tree (CAMU)

♦ Direct integration with Computervision's Product Visualisation System (PVS)

The results of the project will assist Shorts in reaching business objectives by;

- building ease of assembly and maintenance into the product
- determination of most efficient assembly sequence
- reduction in learning time on first article assembly due to improved training
- reduction in number of problems encountered during first article assembly
- reduction in post design changes due to poor maintainability issues
- early visibility of time taken to perform maintenance tasks
- elimination of requirement for a physical mock-up to check maintainability
- reduction in cycle time due to increased concurrency

Examples of the Manakin interaction with the mock-up is shown in Figure 7

Company Systems Integration.

Prior to 1995 , the information systems in Shorts had evolved in a very piecemeal manner producing the cliched "Islands of Automation". There were multiple bills of materials, which were continually being reconciled manually with a variety of formats. In order to address this problem, and provide a single source for each piece of data required , a project was initiated to link all the major systems to-gether. The new system used Digitals Framework Architecture with object broker technology which is Corba compliant. Each application can then communicate to every other one because it has a "Wrapper" which enables it to talk to the other systems. Figure 8 shows an overview of the system and all the major data passing between the applications. EIS is our previously mentioned Executive Information System. EDM is our Optegra Data Management System, Artemis is our project Management System for Design, Capp is our Computer Aided Process Planning System, Maxim is our MRP Scheduling System and Matrix is our ShopFloor control system. If you take the product structure as an example , we can see that it is held within EDM and fed automatically to both our Artemis project planning system and to our Executive Information System.

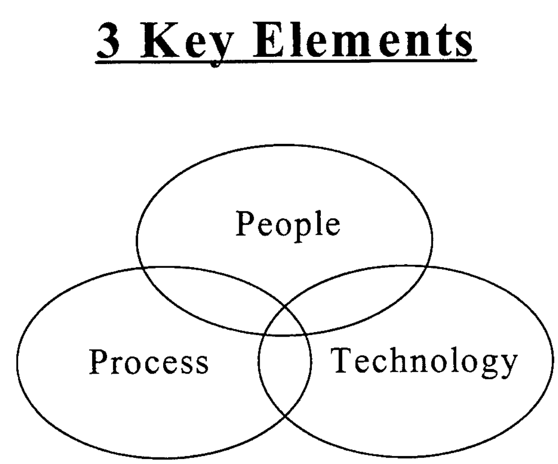


Figure 1

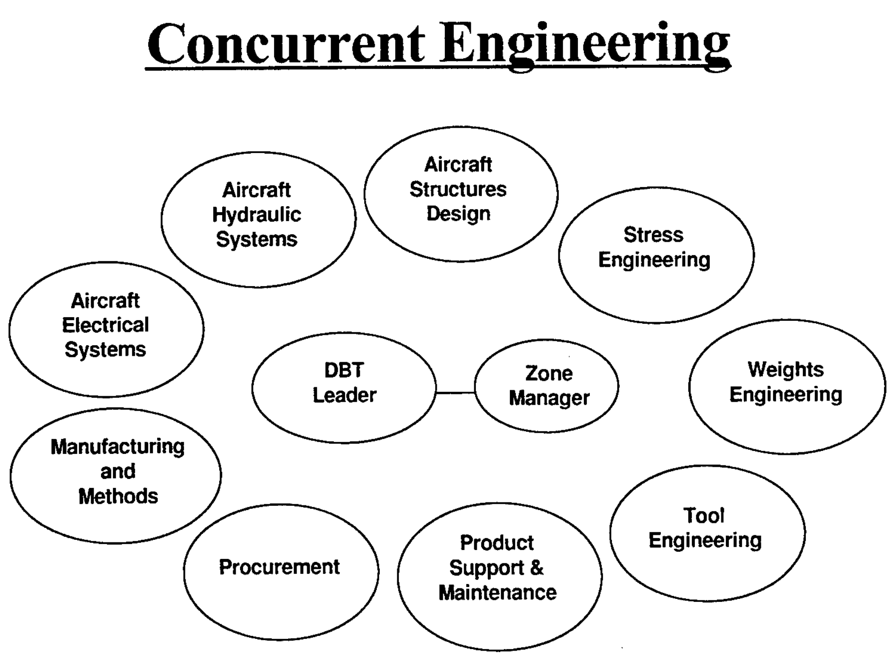


Figure 2

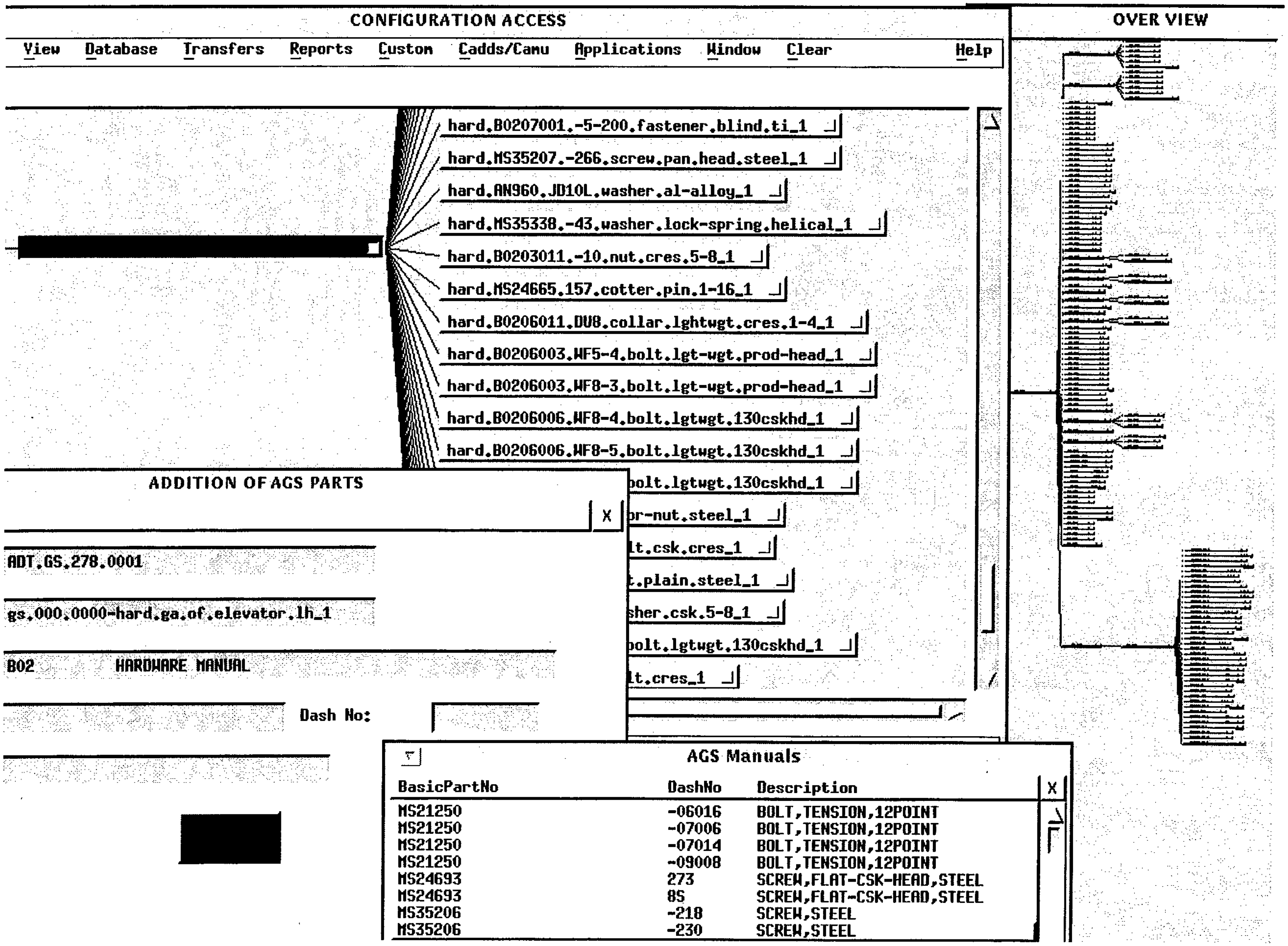

CONFIGURATION ACCESS
View Database Transfers Reports Custom Cadds/Camu Applications Window Clear Help
hard.B0207001.-5-200.fastener.blind.ti_1
hard.MS35207.-266.screw.pan.head.steel_1
hard.AN960.JD10L.washer.al-alloy_1
hard.MS35338.-43.washer.lock-spring.helical_1
hard.B0203011.-10.nut.cres.5-8_1
hard.MS24665.157.cotter.pin.1-16_1
hard.B0206011.DU8.collar.lghtwgt.cres.1-4_1
hard.B0206003.WF5-4.bolt.lgt-wgt.prod-head_1
hard.B0206003.WF8-3.bolt.lgt-wgt.prod-head_1
hard.B0206006.WF8-4.bolt.lgtwgt.130cskhd_1
hard.B0206006.WF8-5.bolt.lgtwgt.130cskhd_1
olt.lgtwgt.130cskhd_1
r-nut.steel_1
t.csk.cres_1
.plain.steel_1
her.csk.5-8_1
olt.lgtwgt.130cskhd_1
t.cres_1
OVER VIEW
ADDITION OF AGS PARTS
X
ADT.GS.278.0001
gs.000.0000-hard.ga.of.elevator.lh_1
B02 HARDWARE MANUAL
Dash No:
AGS Manuals
X
BasicPartNo DashNo Description
MS21250 -06016 BOLT,TENSION,12POINT
MS21250 -07006 BOLT,TENSION,12POINT
MS21250 -07014 BOLT,TENSION,12POINT
MS21250 -09008 BOLT,TENSION,12POINT
MS24693 273 SCREW,FLAT-CSK-HEAD,STEEL
MS24693 8S SCREW,FLAT-CSK-HEAD,STEEL
MS35206 -218 SCREW,STEEL
MS35206 -230 SCREW,STEEL

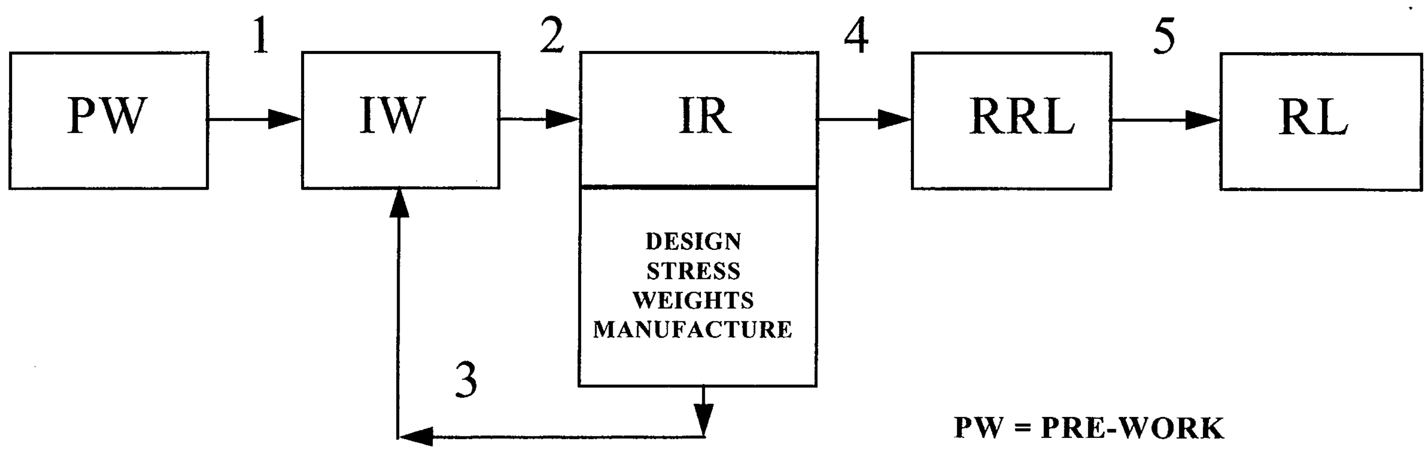
Figure 3

Part Attributes

Drawing Number	Material Dimensions	Pert
Dash Number	To Make Quantity	Grain Flow
Part Description	Made By Centre	Ply ID
Material Specification	Buying Centre	B Number
Used On	Part Category	% Complete
Effectivity	Material Form	Introduced By
Test Effectivity	Material Code	Material Costs
Finished Dimensions	Target Weight	Labour Costs
Similar to Part	Current Weight	
Special Conditions	Actual Weight	
Vendor Part Number	Part Class	
Quantity Per	Unit of Measure	

Figure 4

WORKFLOW PROCESS



PW = PRE-WORK
IW = IN WORK
IR = IN REVIEW
RRL = READY FOR RELEASE
RL = RELEASE

Figure 5

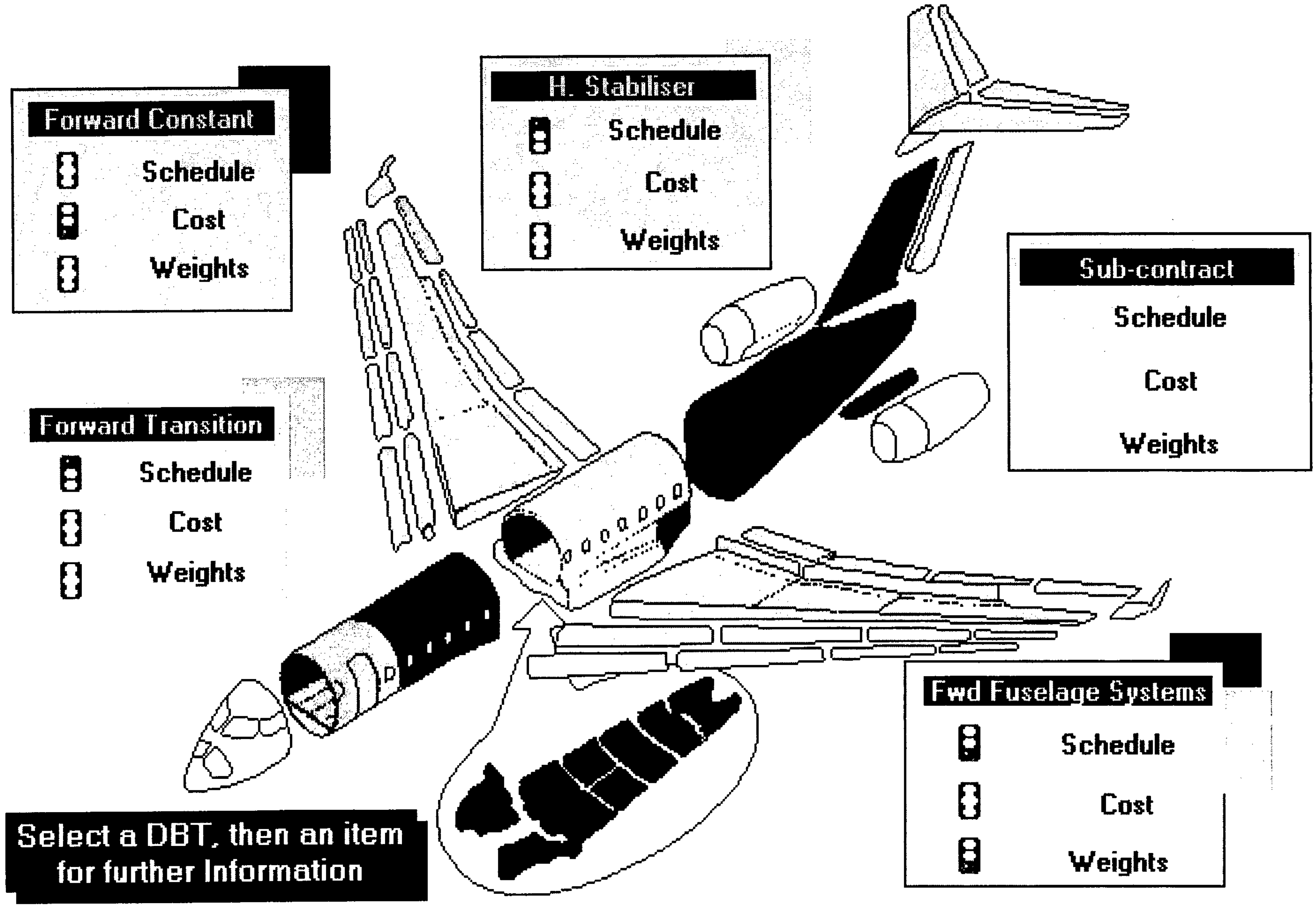

Forward Constant
Schedule
Cost
Weights
H. Stabiliser
Schedule
Cost
Weights
Sub-contract
Schedule
Cost
Weights
Forward Transition
Schedule
Cost
Weights
Fwd Fuselage Systems
Schedule
Cost
Weights
Select a DBT, then an item
for further Information

Figure 6

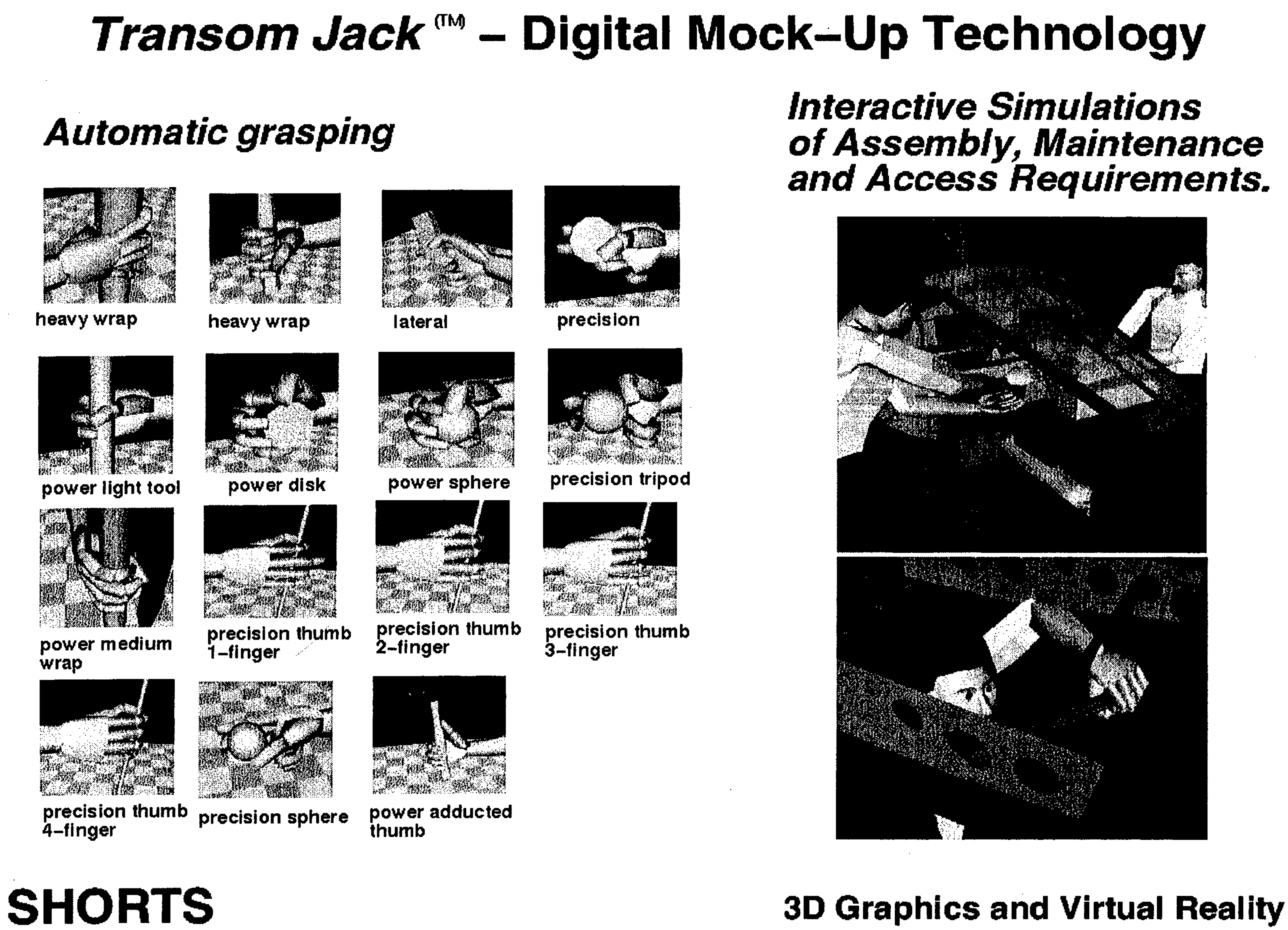

Transom Jack (TM) – Digital Mock–Up Technology
Automatic grasping
heavy wrap
heavy wrap
lateral
precision
power light tool
power disk
power sphere
precision tripod
power medium wrap
precision thumb 1–finger
precision thumb 2–finger
precision thumb 3–finger
precision thumb 4–finger
precision sphere
power adducted thumb
Interactive Simulations of Assembly, Maintenance and Access Requirements.
SHORTS
3D Graphics and Virtual Reality

Figure 7

SYSTEM INTEGRATION

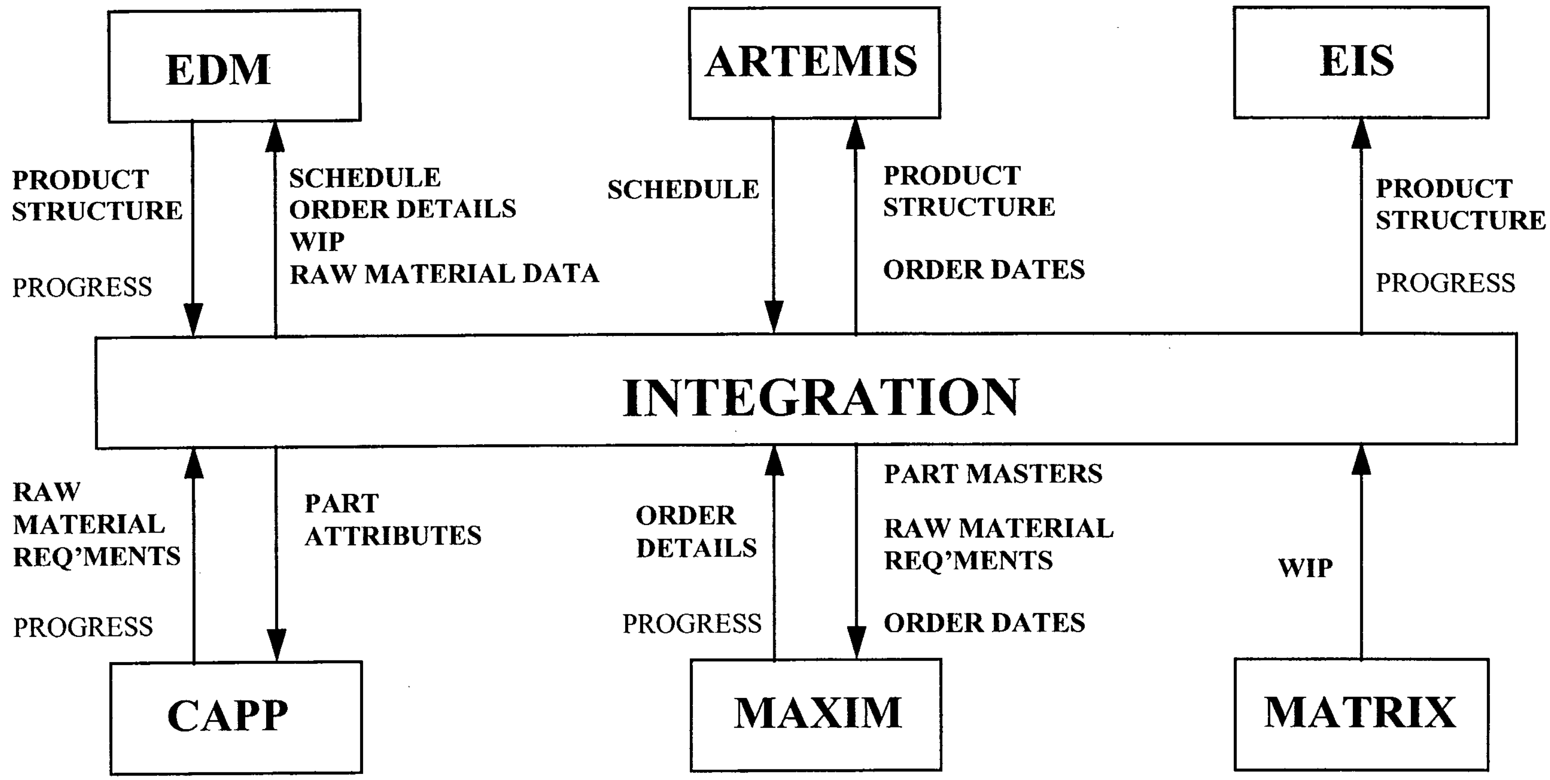


Figure 8

A VIRTUAL RAFALE

Completely Digital Approach for Product and Process

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ABSTRACT

To survive in strong present competition, Dassault Aviation has to ensure a constant update of its organization, management methods and information system. This permanent research has to produce a right compromise between cost, cycle and performances, both for civil and military aircraft.

The Digital Mock-Up (DMU) provides support for Concurrent Engineering (CE) methodologies and contributes directly to customer satisfaction.

In a first part, we will introduce the Dassault's use of CE methodologies as a systematic approach to integrated development of product with the manufacturing processes and customer support. We will emphasize the importance of Teamwork-based decisions, co-specifications, cross-discipline cooperation, efficient communication, change management, simulations...

The second part will be dedicated to CAD/CAM techniques and their extension: Virtual Reality (VR).

We will not mention all the activities related to flight simulators.

RESUME

La survie d'une entreprise du type de la nôtre, passe par la remise en cause continue de son organisation, de ses méthodes de management et de gestion ainsi que des outils informatiques qui y sont utilisés. C'est une recherche permanente qui doit déboucher sur le meilleur compromis coûts, délais, performances que ce soit dans le domaine civil ou militaire. L'ingénierie concourante correspond à cette nécessité. Les conséquences informatiques relatives à la CFAO (Conception et Fabrication Assistées par Ordinateur) et à la " réalité virtuelle " associée sont présentées ici dans la dimension industrielle du programme Rafale.

Les aspects relatifs aux simulateurs de vol ne seront pas évoqués.

A CONCURRENT ENGINEERING APPROACH

The gains necessary for our survival cannot be obtained merely by optimizing the existing industrial structures. A new way of working must take place, it is often referred to as CONCURRENT ENGINEERING.

A typical definition of Concurrent Engineering is :

" A systematic approach to creating a product design that considers in parallel all elements of the product lifecycle from conception of the design to disposal of the product, and in so doing, defines the product, its manufacturing processes, and all other required lifecycle processes such as logistic support.

These activities must be started before all prerequisites are frozen and hence must be adjusted afterwards. In this way, it is possible to do much work in parallel with the main goal to shorten the elapsed time. By powerful computer and communication network support Concurrent Engineering also opens the possibility to test a number of alternative solutions.

Achieving this, the ultimate effort of Concurrent Engineering is to integrate product and process design."

Concurrent engineering contributes directly to the business drivers such as :

- Improved time to market
- Improved product quality and reliability
- Reduced cost of design, development, production and support.

Paper presented at the AGARD SMP Meeting on "Virtual Manufacturing", held in Aalborg, Denmark, 13-14 October 1997, and published in R-821.

In this perspective, a decisive tool is Digital Mock-Up, supporting the effort in modelization and simulation. The result is a decreased risk in the design of a new product.

ORGANISATION

For DASSAULT Aviation, the organization is structured with professions and skills necessary to :

- sell,
- design,
- manufacture and support,
- test and validate

an aircraft.

This organization empowers the technical teams and develops cooperation between programs. To be more efficient in the development of a given program, it was decided to create a dedicated Directorate.

This Directorate is in charge off all synthesis and has to ensure a technical coherence, respecting the contract in terms of performances, cost, cycle and quality.

Since 1990, every actor is reporting both to a technical manager from a hierarchical point of view and to a Program Director from a functional point of view.

This implies a new way of working in internal cooperation.

INFORMATION TECHNOLOGY TOOLS

With the CE approach and the use of "up to date" hardware and software, it is now possible to deliver the right piece of information, at the right time, to the right person, giving to everybody a coherent vision of one project.

Since 1979, CATIA has been used at Dassault Aviation for design and manufacturing activities. At first the problem was to define a single part (mechanical, sheet metal...). We have defined optimized product lines. A product line is characterized as a data flow between activities associated to an aeronautical part category, from design to manufacturing, including quality control inspection and customer services.

Benefits of this global optimization are definitely higher than pure local adjustment or automatization of isolated tasks. Results have been achieved on one hand with a clear settlement of our CAD/CAM use in our business processes (the dissemination of standard rules and procedures among all partners -internally or outside the company) and on the other hand with the development of many dedicated software (integration of our know-how) on the same CATIA platform. We are used to call this approach a vertical integration

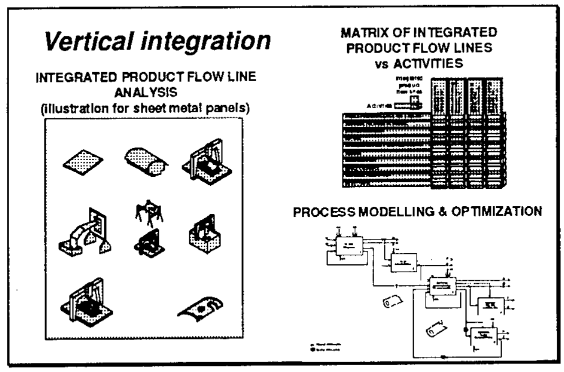

Figure 1 - Integrated Product flow line : from design to manufacturing

Vertical integration is today under control in our company. We are enhancing it with an industrial exploitation of "design by features" which allows us to encapsulate information in entities (features) of the digital definition [FEMOD]. Afterwards, during the manufacturing phase, automatic routines are based on features recognition. Today, "design by feature" is a reality for sheet metal parts at Dassault Aviation.

But now the challenge is to manage not only one part, not only an aircraft, but the whole family of RAFALE (several hundreds).

For the Falcon 2000, RAFALE and the future airplanes, our company has taken the very decisive choice to replace the "physical mock-up" (PMU) by a "digital mock-up" (DMU). Today, DMU specific applications for design, manufacturing and support activities are running on Dassault Aviation sites.

By mean of a large scale digital assembly application, every designer can (as frequently as necessary) search in the database for parts located in a given area. By this way, design development is an iterative cycle starting with the creation of 3D models then checking, revising and sharing the assembly until this one is achieved. This application is based on CATIA Data Management (CDM), in a Relational Data Base environment.

At the design office level, all parts of an aircraft (more than 20.000) are created and DMU is used by every designer who is checking that his layouts fit with those which are concurrently defined by other teams (structure, hydraulics, wire bundles). The user is in position to check for collisions or to analyze accessibility and assembly-disassembly methods without having to rely on physical mock-up. With VR techniques, we are improving our capabilities in visualization and space navigation. It is particularly important when we are working in group (more than ten persons) to validate the definition of some areas. For this occasion, they are persons representing quality control department and some other from the different disciplines involved in the particular area.

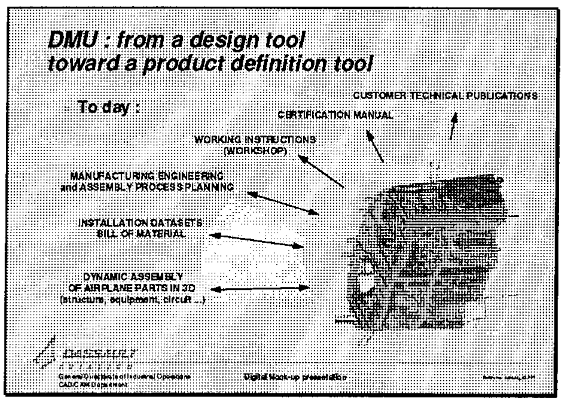

Figure 2 : Digital Mock-UP integration from design to manufacturing

DIGITAL MOCK-UP AND MANUFACTURING PROCESS

Assembly process planning and manufacturing instructions

At the manufacturing engineering level, we have developed a specific application (called SOFIA) which allows the user to build the "as-planned-for_manufacturing" view of the product from the "as-designed" view released in the DMU.

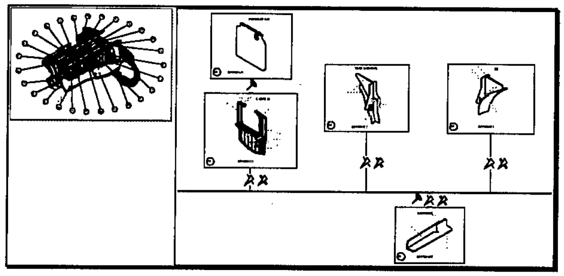

Figure 3 : Step by step validation of an assembly process based on Digital Mock-UP for mechanical parts

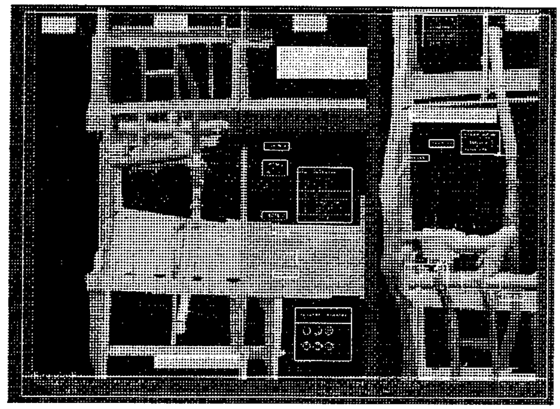

Figure 4 : Mountability validation and Digital Product properties extraction for working instructions

Today, we are exploiting these information for installation datasets, process plans and working instructions for assembly, certification and customer documentation.

Assembly process planning optimization

By mean of a Dassault Systemes's product (called [SCOPES]) we are in a position to manage full associativity between product structure, geometric model and assembly process planning.

The assembly sequence constraints (tubing installation , fixture points...) can be taken into account for optimization.

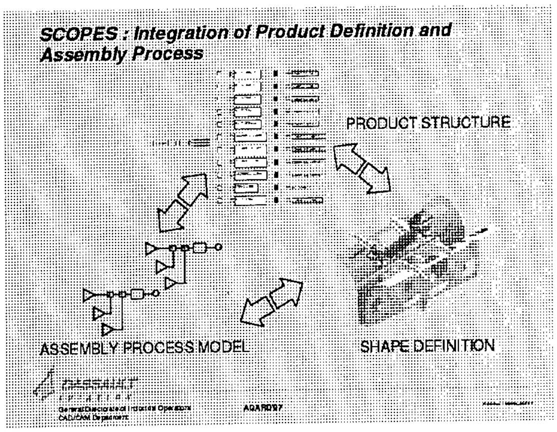

Figure 5 : SCOPES Assembly process planning optimization

More generally, the application domain of SCOPES is the design and control (scheduling, flow control, error recovery, monitoring) of flexible assembly lines.

Advanced Virtual Manufacturing

Current developments of Dassault Systemes integrate the Product Model (structured with a Manufacturing Bill of Material - MBOM); the Industrial Resources Model (structured with a Manufacturing Bill of Resources - BOR) and a Process Model.

Data models are based on STEP. Process model includes product flow, control flow and state diagrams representations.

This integration is a decisive issue for Manufacturing Virtual Execution.

Assembly process and Tooling (jig)

We are developing CAD/CAM applications which connect aircraft product design and preliminary design of assembly jigs.

A jig knowledge base is developed (degrees of freedom of mating features, accessibility criteria...). Kinematics simulation (relative extraction directions of the product after assembly) and interference checking are implemented. This allows an early validation of assembly feasibility.

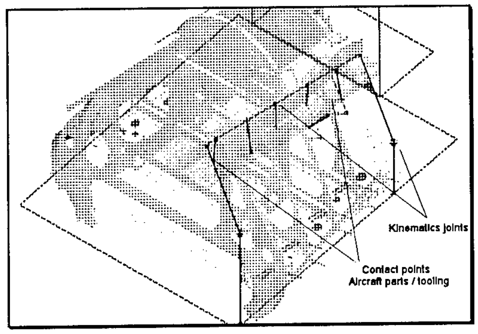

Figure 6 : Rule based feasibility of assembly jig

VIRTUAL PRODUCT MANAGEMENT

This leads to continuously manage through DMU the configuration of each physical airplane "as designed", "as-planned for manufacturing" and "as really built". This management is organized for long term (30 years).

Concerning any extension of our data model, we are focusing on ISO 10303-203 recommendations (STEP AP 203) for product structure and configuration.

To be more efficient we are combining the PDM and the CAD/CAM functionalities in our information system.

We are used to calling this approach an horizontal and vertical integration, because this is dealing both with the different product components and the different stages in the product life cycle.

Our vision for the future of design and manufacturing engineering activities is what we call "an integrated space for definition". The output will be numerical definition of a product and the related manufacturing processes. This data will be the result of cooperation between multiple partners (some of them in Dassault Aviation premises some others outside, in France or abroad). To analyze efficiently this huge amount of data, different techniques will be used, but for the geometrical aspect, the "navigation" with the associated VR techniques will be decisive.

DMU AND VIRTUAL REALITY

Virtual Reality approach

It is possible to characterize VR with 3I [BUR93] : Interactivity, Immersion and Imagination (assistance to solve problems). From our point of view, these features can also be mapped on the following three dimensional diagram [CHED96].

The first horizontal axis supports the fullness level of **information capture** (designer -> system) whereas the second one the fullness level of **information feedback** (system -> designer). This horizontal plane allows a classification of interface technologies. The vertical axis supports the fullness level of **system assistance** (optimization algorithms ...).

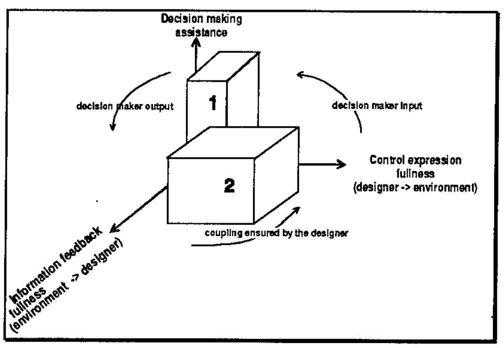

Figure 7 : The Virtual Reality metric

Various VR technologies are becoming available today, however our choices are based on compromises depending on tasks categories.

Tasks related to DMU can be grouped in two categories :

- Create / Share information : Tasks are performed by designers which are familiar to CAD/CAM. Here, emphasis is on system assistance performance. VR solutions are located in the area 1 (vertical high) of the above diagram.
- Review / Global release : These tasks are performed by a group of managers in different disciplines. They are not necessary CAD/CAM experts. Here, emphasis is on interface and VR solutions are located in the area 2 of the above diagram.

Create / Share information

In this case, design environment is composed of ten or so up to two or three hundred parts. Work is calling for a great concentration and skill of the designer during all the work session duration which is quite high (two or three hours).

Creation and modification of geometrical data require interactive access to the CAD/CAM database. Designers are working on 3D exact models. Geometrical consistency and technological rules are continuously checked and executed (for instance, electrical wire bundles curvature is automatically linked to material specifications and checked during design phase).

Due to the great number of stations devoted to this kind of work, we come to the decision of a reasonable cost per unit. Our solution is based on workstations IBM RS6000 connected to a mainframe as a central node (type of mainframe is dependent of the industrial site).

Information necessary for geometry and visualization is processed locally while all information is stored at the central node.

Implementation is performed through an intensive use of CATIA, completed with specific applications developed by Dassault Aviation.

Among these applications we can hold up as examples :

- PACMAN which performs the assembly of different parts of an airplane according to a run-time query based on functional and/or localization criteria.
- ERGO which performs ergonomic simulation of various tasks (from the airplane pilot to the repair worker) and a complement ATTEINTE which solves the accessibility problem to an equipment while improving the quality of the simulated posture.
- various applications for manufacturing which give assistance and sometimes full automatization for manufacturing process planning and programming.

As a conclusion, our action in this domain is rather intended for an optimization of current CAD/CAM solutions. So, virtual reality is rather a new term than a fundamental technological change.

Review / Global release

This case is quite different. New information interface technologies are unavoidable because "mock-up reviews" which were formerly achieved on a physical mock-up at workfloor must be now carried out in dedicated rooms at design office.

The name has been changed from "mock-up review" to "digital assembly review" but the principle to "navigate" in the environment still remains. The project manager is asking for the expertise of the different specialists during common navigation in order to get consensus and validation.

This activity requires a few rooms fitted out with big screens, so investments can be noteworthy. Pure visual feedback will have to be completed with force feedback in order to validate, for instance, assembly or disassembly of heavy equipment.

However, decisions at this step are not immediately executed; they usually presuppose long interventions of CAD/CAM specialists. So, the visualization database may be different from the CAD/CAM database provided reliable updating.

Our action in this domain is still an optimization of CAD/CAM solutions (especially visualization time delay) and furthermore an integration of new simulation tools (datagloves, masterarm, headmounted display...).

The final transparencies will give you an idea about the "reality of this virtual RAFALE".

CONCLUSION

CE techniques use hardware and software as means of communication to help men and women to ensure their mission to sell, design, manufacture and support aircraft. VR techniques enrich this tools.

It is wrong to think that these techniques will reduce the exchanges between persons. On the contrary, they will break some organizational frontiers and decrease the distance effects allowing people to work together.

Many progress are still necessary in DMU and associated Tools and Methods but today it is a reality at Dassault Aviation and will be a competitive advantage for the future.

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Virtual Manufacturing: From Optical Measurement to Rapid Prototyping

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Summary
While a CAD model provides the starting point in conventional „engineering", the process is turned upside down in "reverse engineering", for an existing physical part is the starting point. We have developed an innovative reverse engineering tool providing an efficient link between the real world and the virtual world. Surface-like measuring technology provides „express access" to the world of computer data. Innovative triangulation procedures enable complicated CAD modelling to be circumvented, thus providing a direct transition to production.

Introduction
In view of increasing global competition, one of the greatest challenges facing the Daimler-Benz group is to shorten the development times for its products. The market is demanding more and more product lines for individual world regions, as well as further variants to suit different customer tastes. At the same time, product lifecycles are becoming shorter and shorter.

In 1996 alone, Mercedes-Benz introduced four new product ranges in the form of the T-models in the C- and E-class, the SLK roadster and the V-class. This product offensive is continuing in 1997 with the new M-class, the A-class and in 1998 – among others - with the „Smart" Micro Compact Car. The picture is similar in the group's other business units, whether it be Freightliner, Eurocopter, Airbus or Adtranz.

Such a complex and ambitious product offensive is only possible through employment of highly sophisticated and state-of-the art computer aided development tools, simulation, finite element analysis, digital mock-up, etc.

Within Daimler-Benz in the past a large spectrum of individual tools have been developed and are now in use, for example for studying combustion dynamics, crash properties as well as drive dynamics. Individual tools are now being combined into integrated tools under the names of "RFK" (rechnergestützte Fahrzeugkonzeption – computer aided vehicle concepts) and "NEXT" (next generation development tools).

At the same time, simulation is also used as a support for production planning and optimisation, for example by simulation of stamping processes, spray painting, surface processing or final assembly.

For visualisation of these processes a centralised state-of-the-art virtual reality laboratory has been established within the Daimler-Benz research center.

Reverse Engineering
Thus an increasingly large proportion of development work takes place in the virtual

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data world of the computer. Nonetheless, customers do not want a virtual car but a product which gives them mobility in the real world. This is why an efficient transition between the computer world, with its CAD descriptions, strength calculations or simulations, and the real world of workpieces, tools and products is of elementary importance.

Let us have a look at how transition is nowadays implemented. Engineers design workpieces and the appropriate tooling on a computer screen. These CAD data can then be used e.g. for the production of tools. Through CNC machining, the part in question – in this case the required tool – is produced almost automatically. This process is known as „Computer Aided Manufacturing", or CAM for short.

Changes in part geometry are however a part of the daily routine in a development process. Sometimes these changes can be directly made at the computer stage, but frequently it is only when the part exists in physical form, e.g. after a series of tests, that the need to make corrections becomes apparent. At the same time, the data in the computer need to be updated so that correspondingly modified parts can be produced.

This cyclical transition between the real world of prototypes, workpieces and tools on the one hand, and the virtual computer world on the other, as shown in Fig. 1, is characteristic of product development. Whereas very efficient tools have long existed for optimising procedures in both the real world and the computer world, and computer-aided manufacturing has been carried out for many years, the transition between the real world and the computer world has been a bottleneck costing large amounts of time and money. This is a particular shortcoming when it comes to registering freeformed surfaces.
The remainder of this presentation will focus on this aspect of virtual manufacturing.

At Daimler-Benz research, we have initiated, under the title of "Reverse Engineering", a project to overcome these difficulties, concentrating on two aspects:

- generate fast and complete geometric data of physical parts as an input into the virtual environment
- application of rapid prototyping technologies for fast generation of prototype parts and tools

We focus on the part geometry, not electrical etc. properties. We are thus – in contrast to many other virtual manufacturing applications – working with a geometric model of the part, not with a complete product model.

Optical Measurement Methodologies

On the measurement side we are making use of latest developments in optical measurement techniques which enable the external form of a part to be established very quickly. We have developed a mobile laboratory prototype for 3D shape registration consisting of a fringe projector and one or more electronic cameras with more than one million sensor elements on the camera chip (Fig. 2). This configuration allows the non-tactile registration of several hundred thousand x, y and z coordinates in less than one minute.

The achievable measurement accuracy depends on the size of the measured area. With the current prototype we have achieved a measurement accuracy of 0.1 mm on a measurement volume of 400 mm on the cube, no surface treatment required. We anticipate that until the end of the year 1997 we will have developed a 3D sensor system which is able to measure an entire car with the same precision by automated assembly of partial images. The joining of images is implemented by integrating digital photogrammetry into the 3D measurement system.

The immense progress that this system will achieve is illustrated by a comparison with traditional tactile coordinate measuring techniques:

Coordinate measuring machines are usually located in air-conditioned, vibration-insulated

measuring laboratories. An experienced technician using a tactile measuring unit requires approx. 10 hours to register the complete geometry of a component. If curves and free-formed surfaces are to be described in detail, he must apply a pointer to several thousand individual points on the surface. In comparison, using the newly-developed reverse engineering measuring system the surface shape of the aluminium test body can be completely registered in approx. 10 minutes. This enormous time advantage comes about because tens of thousands of measuring points are taken simultaneously over an area on the basis of just a single view of the object. This process involves the projection of light patterns, e.g. fine fringes, onto the object to be measured. These light patterns are recorded by an electronic camera and converted into three-dimensional geometrical values by a high-performance PC. The individual views, which are also known as point images, are assembled into a continuous overall view by a photogrammetrical process.

Data Handling

Data acquisition is however only the tip of the iceberg. The next challenge is the question of how to handle data sets of millions of points fast and effectively (Fig. 3 and 4). We have developed a process which enables us to generate arbitrary any cross-section of the total data cloud within just a few seconds. Furthermore, we have developed and implemented algorithms to connect the measured surface points in the form of a triangular matrix so as to obtain semi-automatically an initial description of the object's surface. Using a PC, this procedure takes typically half an hour for a complete point image consisting of the order of one hundred thousand points. The resulting triangulated representation of the surface provides the input into CAD modelling as well as CAM and rapid prototyping. We believe that triangulations will become an important alternative to CAD representations in the future. They have the significant advantage of being available much more quickly than CAD models, which take many hours and even days to generate.

Given the triangulated model the computer produces a shaded representation in just a few seconds. This is the interface with „virtual reality“. In future it will however also be possible to produce parts directly from the triangulated model, without using CAD. This not only applies to conventional machining operations such as milling, but also to new, generative manufacturing processes which are referred to as „rapid prototyping“ (RP).

If required for documentation purposes, a CAD representation can of course be generated from the triangulated image.

Applications

As an example from the area of product development, consider the new Daimler-Benz research car, the F200 (Fig. 5). While this car was mostly developed by computer tools, some parts were – for ergonometric reasons – first modelled by hand. An example for this is the sidestick, an innovative tool for steering and controlling the vehicle (Fig. 6). This sidestick - about 20 cm long and containing many free-form surfaces – was digitised in our laboratory in Ulm using the reverse engineering system. The complete measured data set (Fig. 7) consists of 200 000 points, and was taken in 6 individual views, indicated by different colours. The complete measurement took less than 30 minutes. From the data, individual cross sections in arbitrary directions could be generated with few minutes (Fig. 8). Moreover, through automatic triangulation and interactive closure of gaps a closed triangulated mesh of the sidestick was obtained in less than one hour (Fig. 9). This mesh can be used as a basis for stress simulations, as an input for NC path generation for milling as well as duplication by rapid prototyping. Using the Daimler-Benz computer network, data like these can be sent to an in-house rapid prototyping laboratory, processed overnight and delivered to engineers in Sindelfingen the next morning. Through a special converter, the data can be viewed in a virtual reality

environment (Fig. 10). The construction of a CAD model from the data set is somewhat more time-consuming and interactive: using our tools, the CAD model shown in Fig. 11 was generated within 3 hours.

Our measurement system has been adapted to the special needs and working environments of several users within Daimler-Benz.

One example is shown in Fig. 12, an application at Freightliner in Portland: Here, the optical sensor was integrated into a 5 axis milling machine in order to enable measurement of large parts. The user interface was simplified and adapted in such a way that the operator of the milling machine learned the operation of the optical measurement system in less than one day. This system helps Freightliner to substantially shorten development times, especially during the design and prototype phases.

A second example (Fig. 13) is a special measurement system which we deployed at MTU in Munich for the high-accuracy measurement of turbine components. An additional challenge in this application is the fact that the blisks are highly reflective. The pilot system allows the measurement of blisks inside the milling machine, without removing the part, which is of high importance because of the high machining accuracies and expensive machine times involved.

Conclusion

These examples show that the optical technique that we employ is capable to perform reliable measurements both in the design and the production environment. The systems are in operation in several locations within Daimler-Benz; users give fast feedback and guide the further development of Reverse Engineering.

Feedback from our users leads us to believe that a fast Reverse Engineering system brings large advantages in making a fast link between the physical and the virtual world. In spite of the big advantages of virtual manufacturing tools, it turns out that whenever special optimisations are necessary during development, the use of physical prototypes helps to find a better optimum – for example just think of wind channel experiments; and I believe that this will remain this way, at least over the next decade!

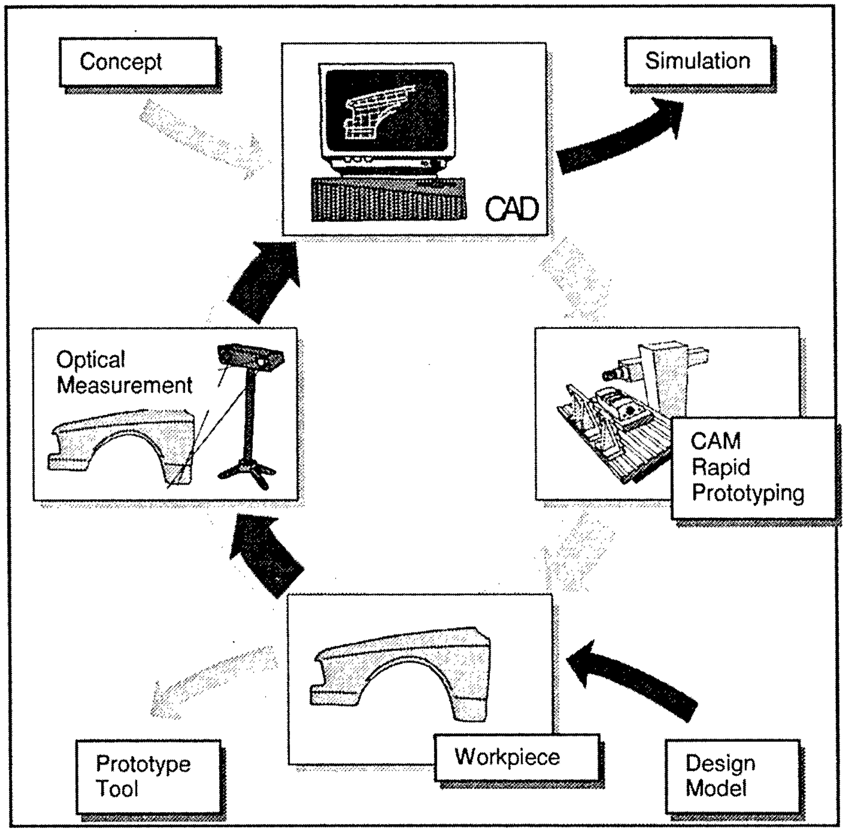

Fig. 1: The "Reverse Engineering" Cycle connects the virtual world with the physical world

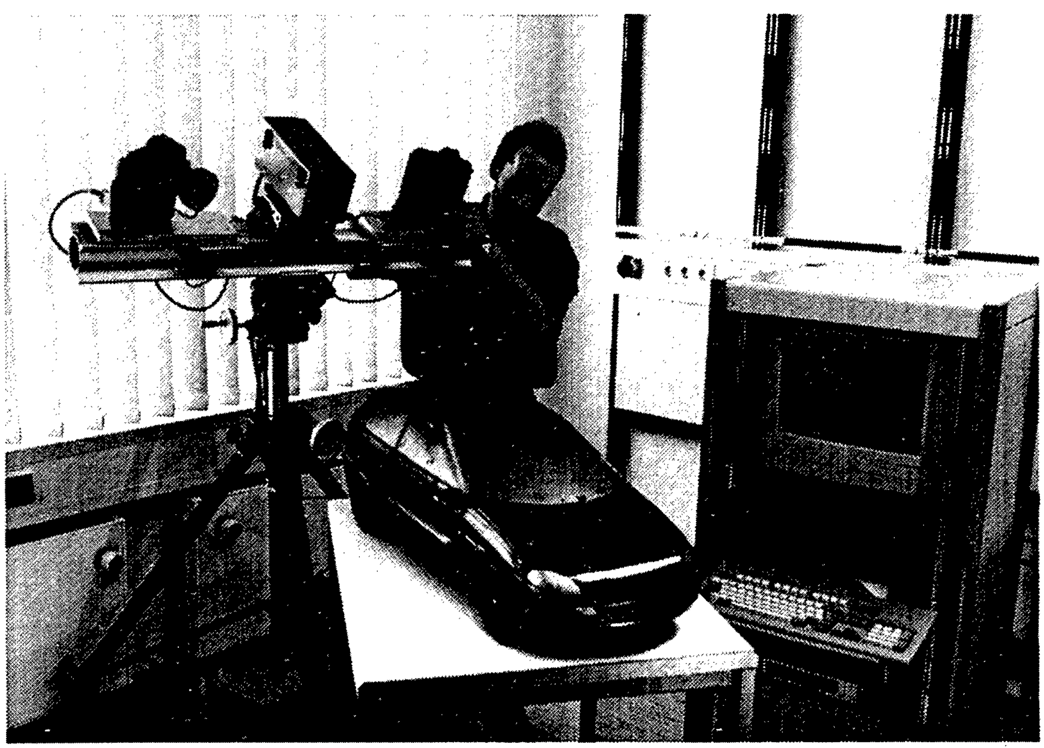

Fig. 2: Prototype optical measurement system for surface-like registration of geometric shapes

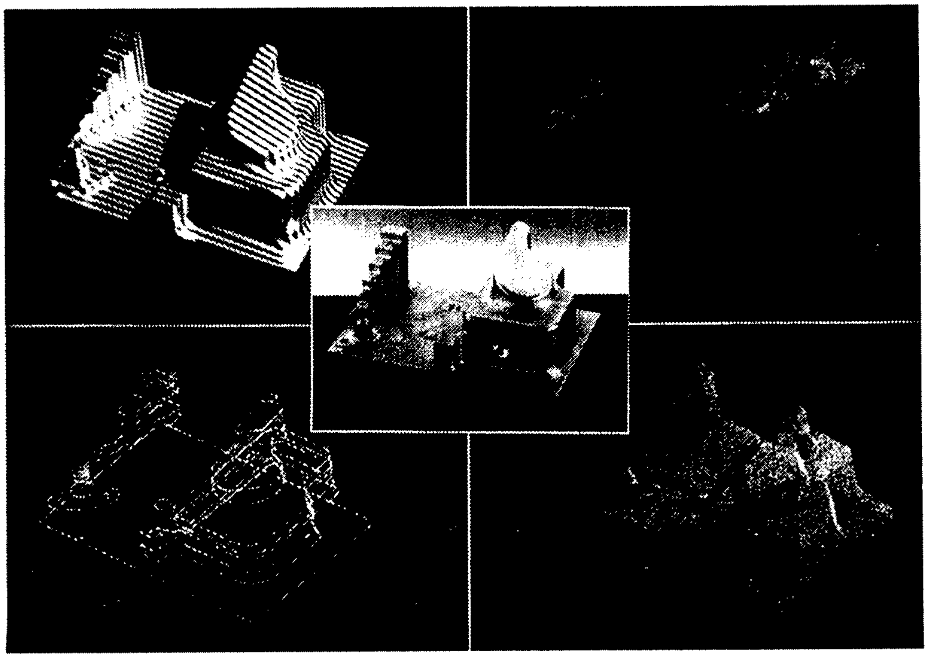

Fig. 3: Steps in optical measurement: a fringe pattern (top left) is projected on the measured object (center). Automatic registration of data sets taken from several individual views (top right) leads to a data cloud of the complete surface (bottom right), from which cross sections in arbitrary directions can be generated (bottom left).

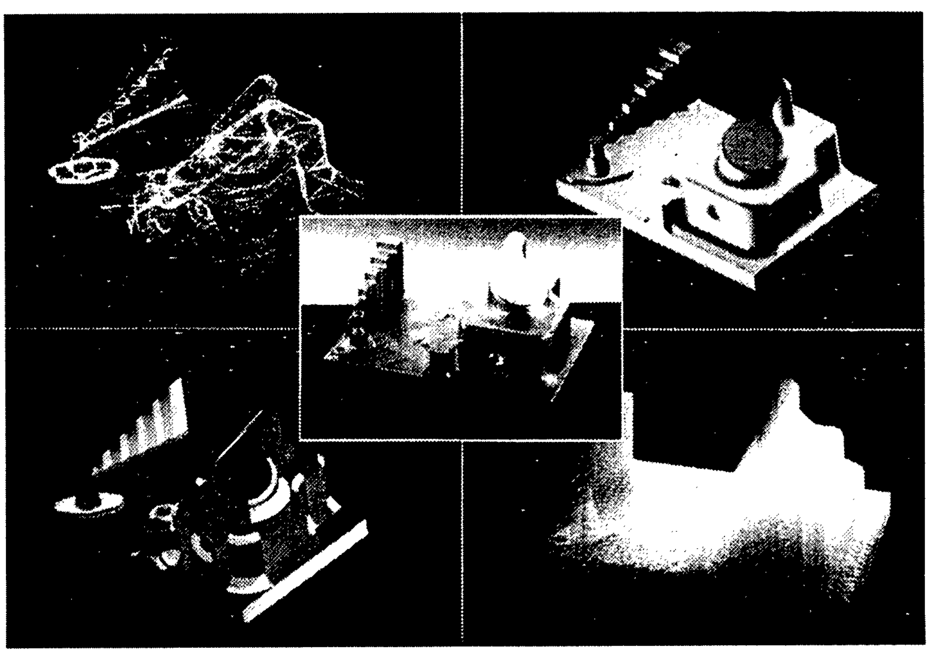

Fig 4: Steps in data processing: The triangulated mesh (top left) of the measured data points leads to a shaded representation (top right) and can be used to build parts via Rapid Prototyping (bottom right). Cross sections are used to interactively build a CAD model (bottom left).

Fig 5: Daimler-Benz research car F200.

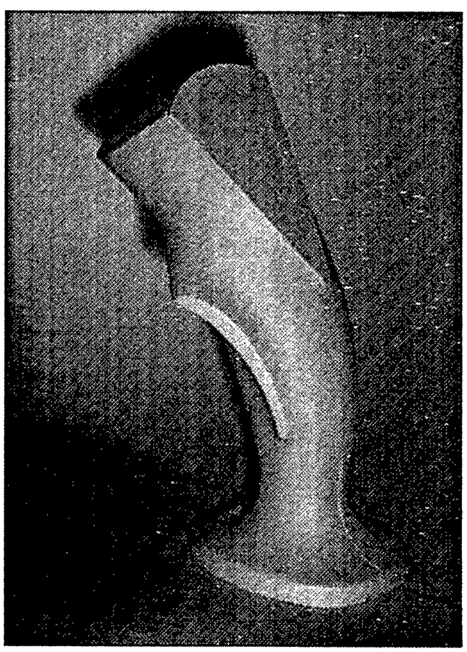

Fig 6: Design model of sidestick used for steering

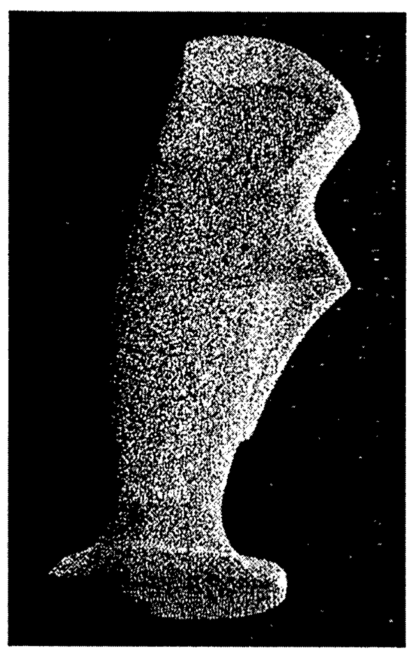

Fig. 7: Point cloud of sidestick, as obtained by optical measurement

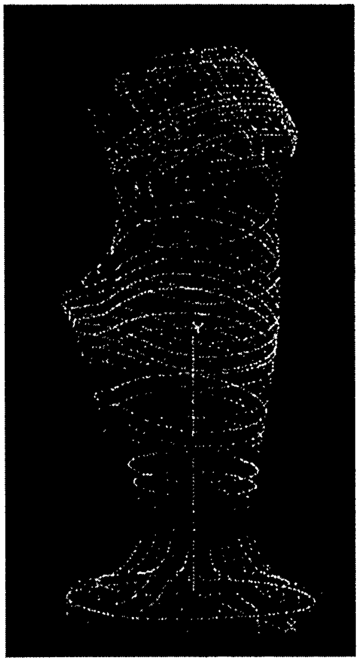

Fig 8: Cross sections in point cloud of Fig. 7.

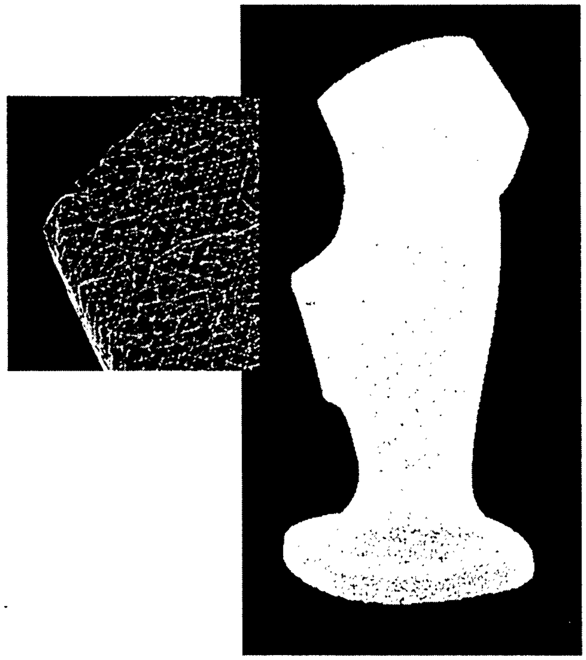

Fig. 9: Triangulated mesh on point cloud of Fig. 7

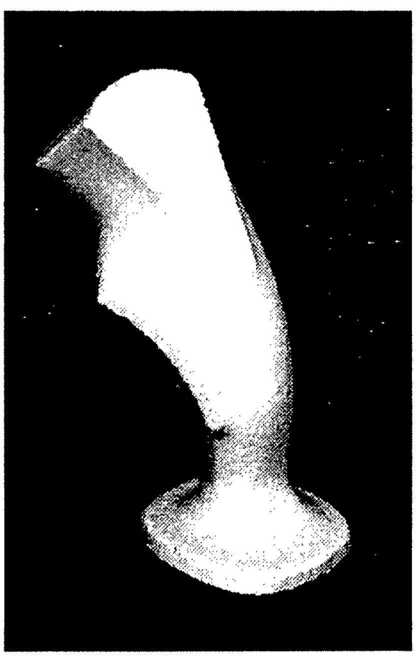

Fig. 10: Virtual Reality representation of sidestick, generated from the data of Fig. 7

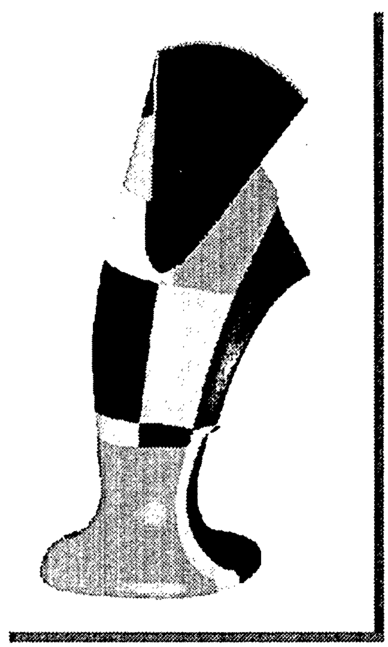

Fig. 11: CAD model of sidestick, generated from the data of Fig. 7

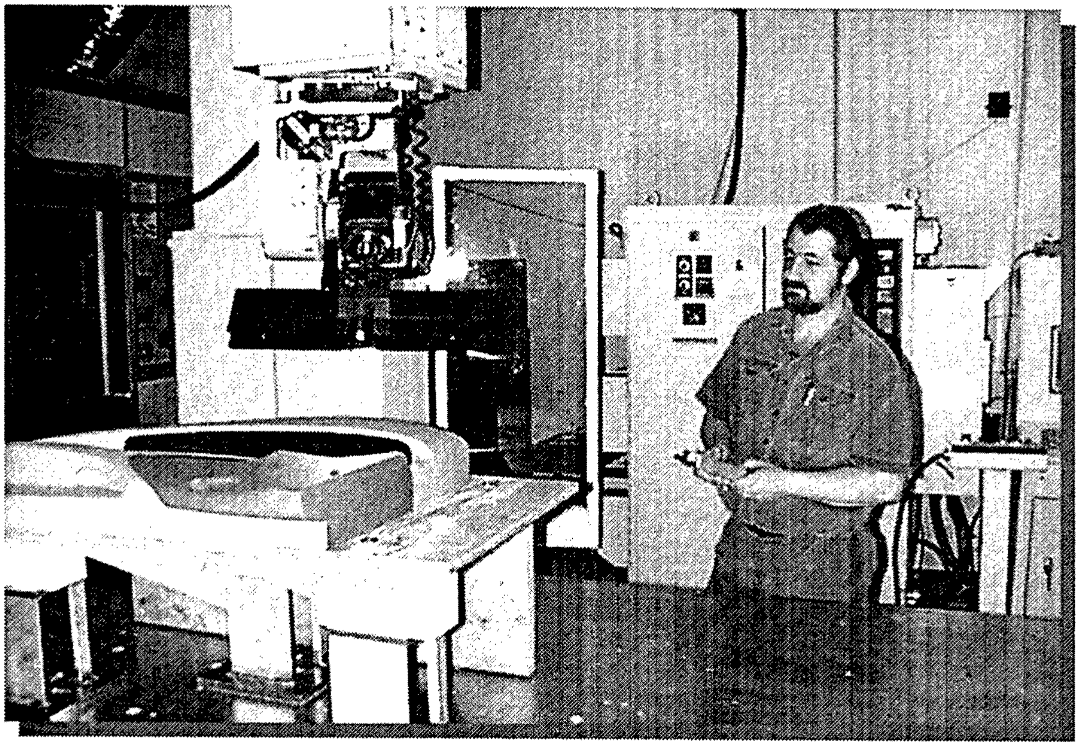

Fig 12: Optical sensor system integrated in a milling machine (Freightliner)

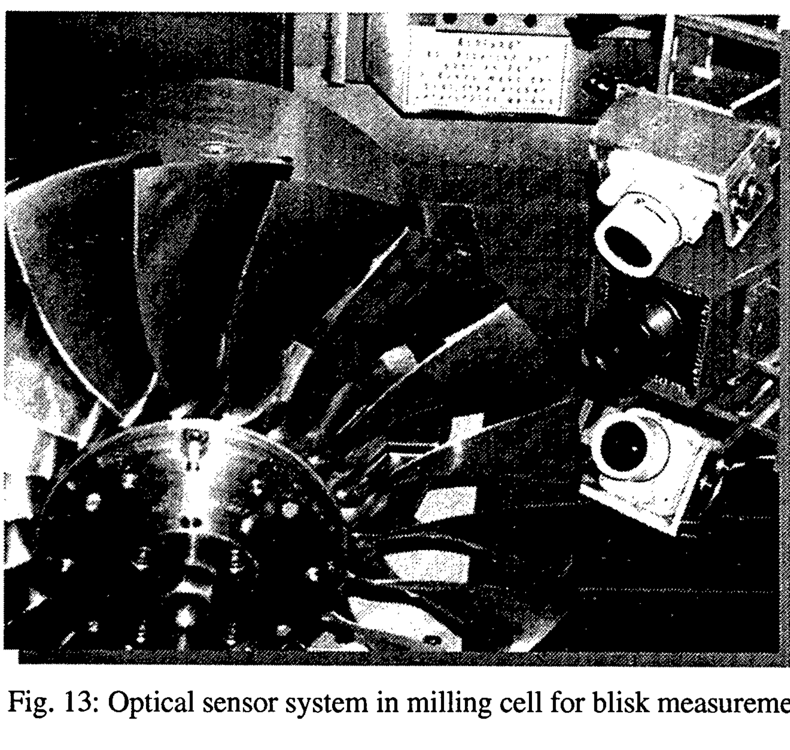

Fig. 13: Optical sensor system in milling cell for blisk measurement (MTU)

Approche Aerospatiale pour la fabrication virtuelle

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abstract
The paper analyse in a first step, Virtual manufacturing deployment within Aerospatiale with the development of information technology tools. It points out the importance of man and the diversity of solutions. This deployment is clearly linked to the main characteristics of Aerospatiale: high technology, human potential stable, skilled and open to innovation, all products developed in a multi-language and cultural partnership. In a second step, the deployment is analysed through a system methodology to derive the main drivers of the deployment. In a last step, the paper presents the research work preparing the next state of deployment. This state will put emphasis on refined product models, distributed virtual manufacturing and semantic based language to improve both people and machine data processing. But as usually the next state will heavily rely on the ability of research work to lead to easy appropriation of new technologies by people and organisation.

1. INTRODUCTION

La production d'avions, de lanceurs, d'hélicoptères, ..., génère de larges flux d'informations techniques et industrielles. Les exigences croissantes en termes de: satisfaction du client, coût total, délai, qualité, respect de réglementations,... impliquent une amélioration constante de la maîtrise de ces flux.

La Fabrication virtuelle a été considérée très tôt comme une innovation majeure dans ce domaine. Elle s'inscrit dans un contexte culturel permanent du Groupe Aerospatiale: haute technologie, potentiel humain stable innovatif et expérimenté, partenariat industriel multi-langues.
Dans ce contexte, une innovation est performante si elle agit sur un chemin critique technico-économique et si elle se prête à une appropriation par les hommes et par les organisations.
La Fabrication virtuelle répond à cette double caractéristique, outil de simulation elle contribue à réduire les coûts et délais, objet visuel elle facilite le dialogue.

2. DOMAINE COUVERT

Dans cet exposé nous avons choisi de rester près de la définition retenue par le "SMP Workshop1": la fabrication virtuelle vue comme un environnement synthétique pour mener l'activité d'ingénierie de fabrication.

Une définition plus large prend en compte
- l'ingénierie du produit associée à une simulation complète du cycle de vie du produit, en considérant que le maintien en conditions opérationnelles et le recyclage prolongent le processus de fabrication,
- la fabrication réelle répartie entre plusieurs ateliers, observée[1] et pilotée comme si elle se déroulait dans un seul atelier virtuel.

3. DÉPLOIEMENT DE LA FABRICATION VIRTUELLE À L'AEROSPATIALE

L'examen de l'impact des technologies de l'information dans les activités de conception et production montre que la fabrication virtuelle est une donnée ancienne pour Aerospatiale et qu'elle s'étend au rythme des progrès des technologies innovantes de l'information.

3.1 l'acquis

Les années 80 marquent l'origine de la fabrication virtuelle pour Aerospatiale avec l'apparition des éléments essentiels que sont les objets virtuels. Le facteur déclenchant a été l'utilisation de la CFAO surfacique et filaire pour produire les plans de définition et pour réaliser les programmes d'usinage des machine à commande numérique.
Le développement de la fabrication virtuelle a été favorisé par l'existence d'une organisation du travail en *groupes opérationnels.* Ces groupes associent, dès la conception, des représentants de bureau d'étude et de fabrication. Ils permettent de prendre en compte au plus tôt les contraintes de fabrication. L'outil CFAO est apparu comme un moyen supérieur au papier pour traduire le résultat du dialogue au sein du groupe opérationnel. L'appropriation de la CFAO par les hommes a été de ce fait assez rapide.

A la fin des années 80, tous les plans de définition de pièces sont réalisés en CFAO. Ces plans permettent de décrire "visuellement" les données fonctionnelles de la pièce, en utilisant les conventions classiques du dessin sur papier (texte, cotation, pointillés,...). Ils décrivent le produit virtuel, de façon formelle, par les contours géométriques à usiner ou à contrôler. La géométrie des contours est par convention (généralement la côte moyenne) celle utilisée pour la programmation numérique d'usinage. Les congés, chanfreins, perçage,... sont choisis pour respecter au mieux les contraintes de production. Plus généralement, le plan CFAO reflète le concept de produit/processus virtuel. Il

[1] via des techniques de réalité virtuelle plutôt que par tableaux de chiffres

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est segmenté en plusieurs niveaux, avec des niveaux ne comportant que des données représentant le "contour" du produit virtuel. Le contour "externe" est séparé des contours "internes". D'autres niveaux sont utilisés pour représenter les états intermédiaires d'un usinage (phases d'enlèvement de matière, de drapage, etc.).

Dans toutes les productions mettant en oeuvre des machines à commande numérique, le fait de disposer de modèles géométriques exploitables directement pour la programmation a fait apparaître un nouveau besoin, celui d'introduire automatiquement les bonnes données technologiques pour générer le programme d'usinage. Le programme de recherche consécutif à ce besoin a traité:

- l'usinage de pièces métalliques par fraisage et tournage en s'appuyant sur un système expert (logiciel COPO) de calcul conditions d'usinage (profondeur de passe, vitesse,...) intégré aux logiciels de génération de trajectoires d'outils,
- le drapage (dépose de ruban et polymérisation) de pièces quasi développables, où parallèlement à la mise au point d'un atelier prototype a été développé son "image virtuelle" (modèle du processus),
- la production de pièces de tôlerie avec mise en panoplie automatique,
- le rivetage automatisé de panneaux,
- ...

Initialement conçue pour aider les hommes à rationaliser et simplifier les tâches de production de "dessins" et de "rubans CN", l'action d'informatisation a été largement acceptée et assimilée par les populations concernées. L'idée qu'il s'agissait d'une nouvelle façon de travailler, basée sur les concepts de produit et fabrication virtuels s'est imposée progressivement. Elle a pris corps à la fin des années 80 avec une réorganisation des ateliers en "lignes technologiques de produits".
Cette vision a été étendue aux partenaires d'Aerospatiale, en particulier au consortium Airbus par la mise en oeuvre de systèmes d'échange de données CFAO. Dans ce but Aerospatiale a développé en 84 un standard d'échange de données SET, devenu norme Française. En complément consciente qu'il fallait aller vers le produit virtuel elle a participé activement au lancement de la norme STEP.

3.2 état actuel

Les années 80 ont permis d'aller assez loin là où les modèles géométriques de produit et fabrication virtuels pouvaient se simplifier en données filaires et surfaciques. Ceci correspond principalement à la production de pièces. Un déséquilibre est alors apparu entre la performance des unités de production de pièces et celle des unités d'assemblages et d'intégration.
L'émergence des technologies de Maquettes Numériques et de CFAO-Robotique a suscité une forte demande. De nouveaux outils sont venus compléter les outils déjà opérationnels. Par exemple ajout de la vision spatiale aux tâches d'étude de flux d'atelier, de prise de pièces, de collisions, d'accessibilité de montage, etc.

Les services rendus par cet enrichissement des modèles de fabrication virtuelle ont été immédiats. Un fort potentiel de progrès existe encore et n'attend que l'évolution des performances des ordinateurs.
Le passage à une simulation "encore plus réaliste" nécessite l'appui de technologues et l'existence de modèles physiques de machines, robots, mannequins, etc. Ce passage a aujourd'hui un coût non négligeable pour un gain aléatoire dans nos ateliers où existe une forte expertise humaine.

Ce problème économique, se retrouve dans la simulation de fabrication de pièces que l'état des moyens informatiques des années 80 n'avait pas permis d'aborder. Citons le cas de pièces obtenues par formage (formage à froid, SPF,...), par injection (composites métalliques ou organiques,...), etc. Ces pièces produites empiriquement ont crée un fort savoir-faire, de faisabilité, d'évaluation de coûts et délais, etc. On peut donc considérer que leur simulation "réaliste et scientifique" (à l'aide de logiciels type éléments finis) n'est pas aujourd'hui sur un chemin critique vis à vis de la performance industrielle globale. Cette simulation reste une affaire de spécialistes en technologie, sollicités au coup par coup. La maîtrise de ces simulations est aujourd'hui principalement assurée par le centre de recherche industriel du Groupe Aerospatiale.

La fabrication virtuelle, telle qu'elle vient d'être décrite, est le résultat du processus d'appropriation, par les *"groupes opérationnels"*, des moyens informatiques des années 80. Ces moyens "centrés" sur le travail individuel et l'échange d'informations ont donné naissance à une organisation en *"filières"* (familles de processus technologiques).
A l'inverse, dans les années 90, l'appropriation des technologies de Maquette Numériques et d'outils du travail collectif a eu pour effet d'élargir le périmètre des groupes opérationnels. Cette évolution a été provoquée par l'émergence de nouveaux concepts d'organisation (Concurrent Engineering et re-ingénierie de processus). Elle a été facilitée du fait que les hommes percevaient non plus des plans et des gammes d'assemblage, mais des produits virtuels et des ateliers virtuels. Les termes "produit" et "atelier" suggèrent implicitement la présence d'autres acteurs (économistes, ergonomes, ...) que les seuls concepteurs et préparateurs.

La première manifestation forte de cette nouvelle vision a été une opération conjointe DASA - Aerospatiale de conception concourante de toilettes en soute. Le travail a été réalisé par une équipe colocalisée multi-métiers, multi-langues de partenaires Airbus. Du point de vue fabrication virtuelle, l'objectif était de créer, sur un avion existant, des toilettes en soute avec un processus minimisant les modifications et le temps d'immobilisation de l'avion. Citons par exemple l'assurance que les outillages peuvent passer par les ouvertures existantes.
Les gains sur le temps de développement ont été suffisament démonstratifs pour passer sur les nouveaux projets, d'une organisation *"groupes opérationnels"*, largement entrée dans les moeurs, à une organisation en *"plateaux"* multi-métiers et multi-partenaires.

4. APPROCHE CONCEPTUELLE DE LA FABRICATION VIRTUELLE

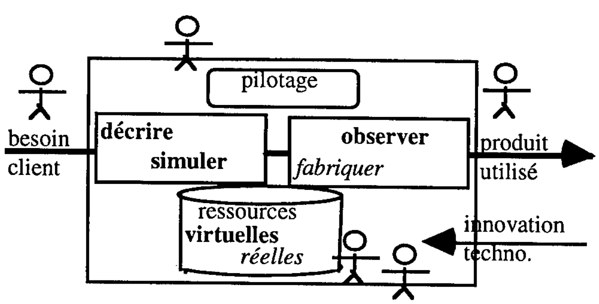
Les points qui se dégagent de la description précédente, sur le déploiement de la fabrication virtuelle, sont d'une part le rôle fondamental de l'homme, et d'autre part la diversité des solutions mises en oeuvre.

Ce dernier point s'explique si l'on examine ce que signifie le mot "produit avion" pour un "vendeur" d'avion, un chef de programme ou un producteur. Pour le premier c'est le résultat d'un processus global qui partant d'une demande génère le produit acheté. Pour le deuxième c'est le fruit du développement et de l'exploitation d'un ensemble de configurations possibles par un ensemble de partenaires. Pour le dernier, c'est un produit parmi d'autres, qui utilise au mieux une partie des ressources de l'entreprise.
Ces trois points de vue correspondent à trois systèmes de conception-production complexes, parfois antagonistes, et qui se recouvrent partiellement.

L'analyse systémique offre un cadre à l'étude du déploiement de la fabrication virtuelle dans ces systèmes, et un canevas pour les évolutions futures.

Cette analyse est esquissée ci-après en trois points:
- un modèle "système de conception-production" qui assimile le virtuel à des objets informatiques,
- l'architecture du système et sa décomposition en sous systèmes,
- l'évolution du virtuel dans l'entreprise avec le développement des technologies de l'information.

4.1 système de conception-production
La mission d'un tel système est d'assurer le bon déroulement du processus de conception et production et de s'adapter à l'évolution technologique. Le croquis ci-dessous schématise ce système



[nota: sur le schéma les caractères en italique repésentent la partie "réelle" du processus, les caractères en gras ce qui relève du virtuel]

Le processus est décomposé en deux grandes phases,
- description et simulation du produit et de son processus de réalisation,
- fabrication (y compris essais) et observation (observation de l'écart entre le produit/processus réel et la description initiale).
L'action des hommes s'effectue au travers d'interfaces homme-système en exploitant des ressources virtuelles et réelles.

La description est destinée
- au client pour l'aider à simuler ou à assurer l'exploitation de son produit,
- aux ateliers pour piloter les machines ou informer les compagnons,
- aux fournisseurs,
- etc.

Une "description" (ou une "observation") obéit à des règles différentes suivant qu'elle est destinée aux hommes ou à la machine:
- consensus entre les hommes sur la signification d'une information,
- cohérence entre le modèle descriptif destiné à la machine et son "image" visuelle ou linguistique destinée à l'homme. Par exemple, un trou fonctionnel et sa séquence de perçage sont associés à un cylindre coloré et à une animation d'outil.
- pertinence des modèles descriptifs vis à vis du besoin de simulation.

Une amélioration du processus est obtenue quand on sait mieux décrire, simuler ou observer, à l'aide de ressources virtuelles appropriées.
Les facteurs de progrès attendus des technologies de l'information sont des innovations sur
- les structures informationnelles (exemple d'évolution: binaire, bases de données géométriques, modèles de données STEP,...),
- les opérateurs (exemple d'évolution : programme binaire,..., programme par tâches),
- les ressources virtuelles (modèles de machines d'atelier, modèles de réglementation, moyens de communication, logiciels experts,...),
- les moyens du dialogue homme monde virtuel,
- la performance des outils informatiques et des réseaux.

4.2 architecture système
Un système complexe de conception-production se décompose en sous systèmes coordonnés et partageant une infrastructure commune.
L'infrastructure comporte un référentiel, des moyens communs, des conventions et normes, un système logistique pour les données et matières, un système de support et adaptation des ressources, etc. Le standard CORBA est un bon exemple d'infrastructure du virtuel.

En se limitant au virtuel, si l'on reprend les trois systèmes identifiés au début du chapitre ("vues" vendeur, programme, producteur), les éléments dominants d'architecture sont respectivement
- gestion projet (ou la gestion de production série) et parallélisation des processus pour améliorer l'écoulement des flux de tâches, sous systèmes regroupant des sous processus,
- gestion de données techniques (PDM) et produit à variantes multiples sur son cycle de vie, sous systèmes "*plateau* multi-disciplines" focalisés sur des sous ensemble du produit (concept de maquette virtuelle multi-configurations, multi-niveaux d'abstraction, multi-composants à intégrer) ,
- gestion des ressources d'entreprise (ERP) et utilisation optimale des connaissances, sous systèmes "*filière*" (unité de conception-production par technologie), qui résultent d'une analyse technologie de groupe.

Dans la pratique, ces diverses architectures ont des caractères mixtes et dans un même système global on trouvera des sous systèmes organisés en plateau ou par filière.
Cette souplesse exprime le fait qu'un sous système

peut appartenir[1] à plusieurs systèmes de conception-production.

Dans l'organisation Aerospatiale, on trouvera à la fois une organisation par *plateaux* autour de grands sous ensembles et une organisation par *filières*. Par exemple, en ce qui concerne AIRBUS, Aerospatiale et ses partenaires ont adopté dans leur programme ACE (Airbus Concurrent Engineering) [Azon] une décomposition en grands sous systèmes jouant à la fois sur le produit et les moyens de production (configuration générale avion, définition système, structure-installation systèmes, familles technologiques de composants, support client). L'infrastructure s'appuie sur un couple SGDT - CFAO commun aux partenaires.

Un sous système répond à trois critères: il doit être relativement autonome, globalement stable dans le temps, et être intégré dans le système global.

Le critère stabilité permet d'investir dans le développement de ressources locales type experts métier, machines spécialisées, bases de connaissances,...

L'analyse de la décomposition en sous systèmes *filière* et les investissements à réaliser en matière de fabrication virtuelle peuvent être traduits par une matrice. En horizontal on identifie des logiciels communs ou non à plusieurs filières technologiques, en vertical ces logiciels sont intégrés en un outil adapté à un sous système particulier. Cette intégration permet en particulier de pousser très loin l'utilisation de l'outil informatique pour assurer les étapes description, simulation, observation du processus de conception-production (cf schéma §4.1).

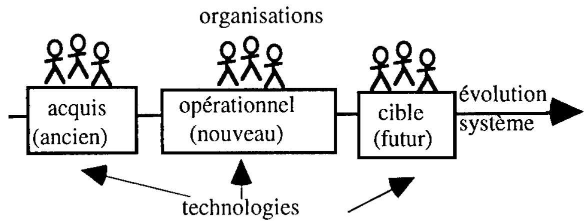
- technologies - -activités virt. -	integr produit complexe	grands assemb	petits assemb	tubes	SPF	etc.
proto virtuel rap. prod/process (dimensionnemt)						
def produit virt.						
routes & transferts						
outillage						
process usinage						
process de contrl						
ordo. de process						
pilotage process						
format. personnel						

nota 1: L'activité prototypage virtuel rapide sert au dimensionnement général et à l'évaluation macroscopique de fabrication. L'activité définition produit s'exécute en intégrant les contraintes aval de fabrication, contrôle, maintenabilité,...(design for Xabilities).

nota 2: Les activités "process" comportent deux volets, le premier étudie le domaine de faisabilité, le deuxième détermine la meilleure stratégie pour un cas de fonctionnement particulier. Par exemple dans le cas d'usinage de pièces en Panoplie, l'usinabilité de chaque pièce sera étudiée à l'aide de connaissances expertes. L'imbrication sera réalisée en temps réel par un algorithme génétique en fonction des priorités de production.

4.3 gestion de l'évolution des systèmes

L'introduction d'innovations majeures dans un système nécessite une gestion appropriée illustrée par le schéma ci-dessous. Ce schéma distingue trois états du système, un état stabilisation d'existant (les bases de référence de migration), un état mise en oeuvre/exploitation d'organisations et technologies matures, un état cible future.



Au plan humain cette décomposition facilite les évolutions d'organisation et l'appropriation des nouvelles technologies.
Les trois états permettent de comprendre en quoi le nouveau système mis en oeuvre est dans la continuité de l'ancien, et pourquoi il constitue une étape raisonnable vers un futur plus ambitieux.

L'évolution technologique et humaine d'un système global se fait à la fois sur les sous systèmes et sur l'infrastructure. Une partie du système ancien persiste dans le nouveau système, et des éléments du futur sont déjà opérationnels. Le tableau ci-après, qui reprend les grands constituants d'un système (cf §4.1), illustre l'évolution de la fabrication virtuelle en prenant des exemples d'innovations pour les trois états.

	acquis/ancien	opérationnel/nouveau	cible/futur
PPV structure info. (Produit/Processus Virtuels)	*filaire surface attributs*	*solide + liens logiques geom maillée entité-relation*	*features objets*
PPV operateurs	*"rubans CN"*	*tâches(macro op) logiciels de simul*	*smart operators agents*
machines virtuelles	*fonctionnelles*	*"spatiales"*	*"technologiques"*
communication et processus	*échange point à point*	*échange en réseau*	*partage*
connaissance	*système expert*	*CFAO à base de connaissances*	*distribuée dynamique*
présentation	*graphique, texte*	*volumique, couleur*	*réalité virtuelle langage naturel*
org humaine	*groupe opérationnel*	*plateau colocalisé*	*plateau distribué*

4.4 synthèse

L'approche système de conception-production est globale, abstraite et structurante. Elle permet d'exprimer que la finalité de la fabrication virtuelle n'est pas de construire des modèles virtuels, mais de répondre au mieux aux interrogations relatives à l'industrialisation des produits et processus. Ces interrogations portent sur les configurations possibles, les variantes, les découpages industriels, la faisabilité, l'accessibilité, le coût, le temps,....

L'approche système est dynamique, qu'il s'agisse du comportement du système face à une sollicitation externe ou de son aptitude à évoluer. Cette dynamique est essentiellement assurée par les hommes. Dans un environnement très changeant il convient de partir de l'élément humain pour déterminer quelles innovations technologiques améliorent le système. C'est le choix d'Aerospatiale depuis de nombreuses années.

[1] L'appartenance à plusieurs systèmes ayant des infrastructures incompatibles pose un problème d'interopérabilité.

En résumé, l'approche système constitue un bon outil d'aide à la maîtrise du déploiement actuel et futur de la fabrication virtuelle.

5. ÉTAT FUTUR ET RECHERCHE

Cet état correspond à des avancées significatives sur la valeur des paramètres clé des systèmes de conception-production. Il détermine les objectifs de la recherche et tient compte des caractéristiques fortes d'Aerospatiale: une communauté stable d'hommes expérimentés et ouverts au changement, une longue durée de vie des produits, un partage de ressources entre divers programmes aéronautiques, un partenariat industriel multilangues et multicultures.

Les travaux de recherche préparent l'appropriation des innovations par les hommes de l'entreprise. Ils sont menés avec d'autres industriels et des fournisseurs de logiciel. Cette logique de coopération est guidée par l'émergence d'une société de la communication. Elle est conforme à la tradition du Groupe Aerospatiale qui développe en mode partenariat tous ses produits: avions, lanceurs, hélicoptères, etc.

La recherche est tirée par les grandes tendances technologiques:

- le développement rapide de réseaux à haute performance, ce qui signifie que la fabrication virtuelle peut être distribuée dynamiquement entre divers sites spécialistes contrairement à la fabrication réelle qui est géographique,
- l'aptitude à manipuler un nombre toujours plus grand de données, ce qui signifie que les contraintes "volume de données et vitesse de traitement" ne sont pas des critères stables pour découper un système de conception-production en sous systèmes,
- la réalité virtuelle et les hypermedias qui modifient profondément le dialogue homme-système et entre les hommes, donc le pilotage des objets virtuels et réels,
- la représentation, le traitement et la gestion des données techniques, des connaissances, des événements,... qui amène à repenser modèles de ressources (ou de services) et d'objets virtuels.

à ces tendances sont associés des thèmes de la fabrication virtuelle:

- utilisation des technologies CORBA, STEP, Internet pour le partage des données maquettes et des moyens virtuels entre partenaires [Feru],
- développement de méthodes de conception et exploitation multi-métier des maquettes virtuelles avec en particulier prise en compte des tolérances [Mar],
- développement de méthodes et prototypes pour naviguer intuitivement dans les données produit ou processus, et pour annoter ces données [Graux],
- étude de l'aptitude de techniques cognitives à décrire les produits et processus virtuels, modélisation par features, raisonnement par cas,...

Les trois premiers thèmes s'appuient sur la forme géométrique et le mouvement des objets, c'est en quelque sorte une extension de la CFAO classique. Citons les projets européens ESPRIT-RISESTEP[1] pour les maquettes distribuées, BRITE DMU-MM et CEDIX pour la modélisation et l'exploitation des maquettes virtuelles, BRITE DMU-VI pour l'interface homme-système virtuel.

Le dernier thème, plus ambitieux, base la fabrication virtuelle sur la représentation et le partage des connaissances métier en exploitant les possibiltés offertes par la technologie objet. On peut citer les projets BRITE FEMOD et FEAST de modélisation de pièces et liens d'assemblage par "features[2] sémantiques et géométriques". Cette modélisation permet de décrire le produit et son processus de production à l'aide d'un "langage" technique compréhensible par l'homme et exploitable par la machine à des fin de gestion et simulation. Un autre intérêt, est que ce langage améliore la qualité de l'échange d'informations entre partenaires multi-langues.

En parallèle à ces activités communication d'information et exploitation des connaissances, les progrès en puissance de calcul et en logiciels à éléments finis accélèrent le développement de la simulation scientifique des procédés et moyens de fabrication. Quatre directions sont abordées :

- améliorer la qualité des modèles par la recherche technologique,
- faciliter l'exploitation des outils de modélisation et simulation,
- utiliser les modèles dans les moyens de fabrication pour améliorer le pilotage et gérer le retour d'expérience,
- intégrer ces outils et méthodes dans l'environnement opérationnel.

Le cas du drapage par dépose de tissus illustre ce dernier thème. Les ateliers de drapage ont fait l'objet, dans les années 80, d'une modélisation pour la simulation avec une exception majeure: l'étude de la mise en forme des tissus qui est restée expérimentale. Les travaux récents [Blanlot] sur la simulation scientifique de la déformation de tissus pré imprégnés vont combler cette lacune. Toutefois, l'intégration de l'outil de simulation dans l'environnement opérationnel ne signifiera pas le simple remplacement d'une tâche empirique, mais efficace, de dépose et découpe de tissus. Le gain économique serait probablement faible. L'objectif sera de tirer profit d'informations nouvelles telles les données locales de déformation, la valeur des forces à exercer, l'orientation des mèches, ... Ici encore, le succès du passage au virtuel sera directement lié à son apport pour l'homme.

6. CONCLUSION ET PERSPECTIVES

Nous nous sommes attachés dans ce texte à montrer que la Fabrication virtuelle n'est pas une simple démarche technologique. Elle relève d'une appropriation par les hommes d'Aerospatiale d'éléments innovants pour mieux exercer leurs activités industrielles "immatérielles".

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[1] le projet correspond à une implémentation de systèmes de conception-production distribués

[2] feature: structure récurrente d'information. Le terme récurrent précise que l'objet informationnel est stable dans la vie de l'entreprise et justifie un investissement pour être modélisé avec plus ou moins de précision.

La Fabrication virtuelle vise:
- à mieux communiquer et partager la connaissance du problème à résoudre et des moyens pour y arriver, et d'autre part,
- à se doter d'outils pour simuler des points délicats plutôt que recourir à des expériences physiques si elles sont longues ou onéreuses.

Les performances toujours croissantes des outils de traitement de l'information conduisent à penser que la simulation de la fabrication sera de plus en plus proche de la "réalité industrielle" réduisant les besoins d'expérimentation pratique.
Toutefois c'est du coté des moyens de communication et celui du partage des connaissances que sont attendus les plus grands gains. En effet, ils vont permettre à un nombre accru d'acteurs, y compris de l'atelier, de donner leur point de vue, et ce très tôt dans le processus de décision. Cet aspect des choses est encore difficile à appréhender après des décennies passées à développer des méthodes et modèles adaptés au travail d'individus ou d'équipes isolés dans leur bureau. Approche systémique et appropriation humaine seront les clés de cette nouvelle étape du déploiement de la fabrication virtuelle

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Simulation Assessment Validation Environment (SAVE) Reducing Cost and Risk Through Virtual Manufacturing

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1. SUMMARY
The 1994 Lean Aircraft Initiative industry forum, identified the application of Virtual Manufacturing (VM), in the form of integrated simulation technologies, as a key technology in reducing cost and increasing quality. The Joint Strike Fighter Program initiated the Simulation Assessment Validation Environment (SAVE) Program to integrate a set of VM tools and to validate the potential savings through a series of demonstrations. This paper describes the SAVE program and its potential for a $3 Billion (US) savings on the Joint Strike Fighter program.

2. INTRODUCTION
Virtual Manufacturing (VM) is the integrated use of design and production models and simulations to support accurate cost, schedule and risk analysis. These modeling and simulation capabilities allow decision makers to rapidly and accurately determine production impact of product/process alternatives through integrating actual design and production functions with next generation simulation. The use of simulation software to achieve the objectives of virtual manufacturing has been rapidly increasing throughout industry. The potential for these tools to significantly improve affordability and reduce cycle times is widely accepted, but the potential has not been fully achieved.

Many commercial manufacturing simulation tools with excellent capabilities exist on the market today. Although, many of these tools rely on similar types of data, differences in internal storage structures and nomenclature have prevented easy tool to tool data integration. Often, large amounts of data must be reentered, at considerable time and expense, to accommodate these differing formats. Some point to point solutions do exist between specific tools, but as the number of tools grows, this integration solution becomes unmanageable, and the benefits from using an integrated tool suite go unrealized.

The Simulation Assessment Validation Environment (SAVE) program, underway at Lockheed Martin and funded through the Joint Strike Fighter Program Office, is addressing these limitations by developing and implementing an open architecture environment to integrate modeling and simulation tools and by demonstrating this integrated simulation capability to significantly reduce weapon system life cycle costs (LCC).

Paper presented at the AGARD SMP Meeting on "Virtual Manufacturing", held in Aalborg, Denmark, 13-14 October 1997, and published in R-821.

The initial phase of the program, completed in August 1996, established a core tool suite integrated via the Defense Advanced Research Projects Agency (DARPA) developed Rapid Prototyping of Application Specific Signal Processors (RASSP) architecture. The core tool suite incorporates commercial CAD, factory simulation, assembly simulation, cost and risk modeling capabilities. Through the 4 year span of the effort, both the level of tool-to-tool communication and number of tool types will be expanded. Benefits will be validated though a series of demonstrations focused on both the F-16 and F-22.

3. OBJECTIVES OF SAVE

In recent years, manufacturing modeling and simulation software has seen increased use throughout industry. Rapid advances in computing hardware and software now allow accurate simulations of complex processes. Computer graphics provide Integrated Product/Process Teams (IPPT) with the means to efficiently understand the results of these simulations and make critical design and manufacturing decisions, without resorting to costly physical prototypes.

Growth in the use of virtual manufacturing tools has only been limited by the costly, manual transfer of data among the set of simulation tools. Typically, a design team will use a 2-D or 3-D CAD package for design. The team will then assess the manufacturing impact of product and process decisions through use of a set of virtual manufacturing tools to assess cost, schedule, and risk. The tool capabilities typically include :

- Process planning
- Dimension and tolerance analysis
- Schedule simulation
- Assembly simulation
- Factory simulation
- Ergonomic simulation
- Feature-based costing

These tools use much of the same data as input, but each require different internal data formats. Manual reformatting and reentry of these data are prohibitively costly.

In 1994, a U.S. Government led Lean Forum Workshop reached consensus on a set of critical investment areas focused on overall weapon system affordability. These areas included:

- Integrated design and cost
- Modeling and simulation
- Teaming
- Factory Operations
- Design for quality and producibility

Based on this Government/Industry consensus, the Joint Strike Fighter program office initiated the SAVE program. The objective of SAVE is to demonstrate, validate and implement integrated modeling and simulation tools and methods used to assess the impacts on manufacturing of product/process decisions early in the development process. The key anticipated results of the SAVE program are the demonstration of an initial Virtual Manufacturing capability, and the validation of this capability to reduce the maturation costs and risks associated with the transition of advanced product and process technologies into production.

Understanding the development process metrics impacted by SAVE is central to managing SAVE development to achieve the maximum improvements in these metrics. The following product/process metrics were selected to guide SAVE development:

Design to cost data accuracy - accurate cost prediction improves design decisions and requires fewer iterations to achieve desired cost

Lead time reduction - provides for process optimization leading to better schedules and closer to just-in-time factory

Design change reduction - improved, affordable designs with fewer errors reduces need for late design changes

Scrap, rework, repair reduction - many product / process problems identified prior to design release, not on shop floor

Process capability - processes that control key characteristics of critical parts and assemblies can be analyzed for their cost impacts

Inventory turn time reduction - factory processes and layout are optimized through simulation to provide better just-in-time performance

Fabrication & assembly inspection reduction - designed-in quality verified through simulation reduces need for separate inspection operations

Early in the SAVE program the proposed capability and approach of the SAVE solution were described to members of the Integrated Product/Process Teams working on the F-22 Advanced Tactical Fighter. These active design teams estimated the significant potential benefits, shown in Figure 1, for the proposed SAVE integrated virtual manufacturing system. Adjustments were made for the Joint Strike Fighter Program based on differences in acquisition programs and design phases.

As a result of the SAVE Program's enhanced virtual design and manufacturing environment, and tools, the program's benefits forecast a potential savings of 1 percent to the F-22 current air vehicle average unit cost, or approximately $716K per aircraft. For a new acquisition system like JSF, the potential benefits are projected to be 2% - 3% of the total Life Cycle Cost - a total cost avoidance of over $3B.

PRODUCT / PROCESS METRIC	SAVE Impact To Metric (%)	
	F-22	JSF
Design to Cost Data Accuracy	25	12
Lead Time Reduction	5	10
Design Change Reduction	15	28
Scrap, Rework & Repair Reduction	15	11
Process Capability	10	5
Inventory Turn Reduction	5	2
Fab & Assy Inspection Reduction	13	6

Figure 1. SAVE Affordability Metrics

4. TECHNICAL APPROACH TO SAVE

The SAVE program encompasses five distinct elements :

1. Simulation tool integration
2. Tool execution infrastructure
3. Feature-based cost models
4. Demonstrations
5. Implementation / commercialization planning

Elements 1 through 3 are discussed in this section. Elements 4 and 5 are described in Section 5.

4.1 Tool Integration

The SAVE program approach to tool integration and overall infrastructure is shown in Figure 2. Major elements of this architecture include the classes of manufacturing simulation codes, Common Object Request Broker Architecture (CORBA) compliant code "wrappers", the SAVE Data Server, a Work Flow Manager (with its NetBuilder graphical programming interface), a web-based data browser, an Electronic Design Notebook, and back-end data storage systems (tailored to each implementation). A SAVE common desktop provides a standard interface to the system, independent of computing platform.

The simulation tool classes shown in Figure 2 are used to assess the cost, schedule, and risk of product and process design decisions. The SAVE system supports a range of

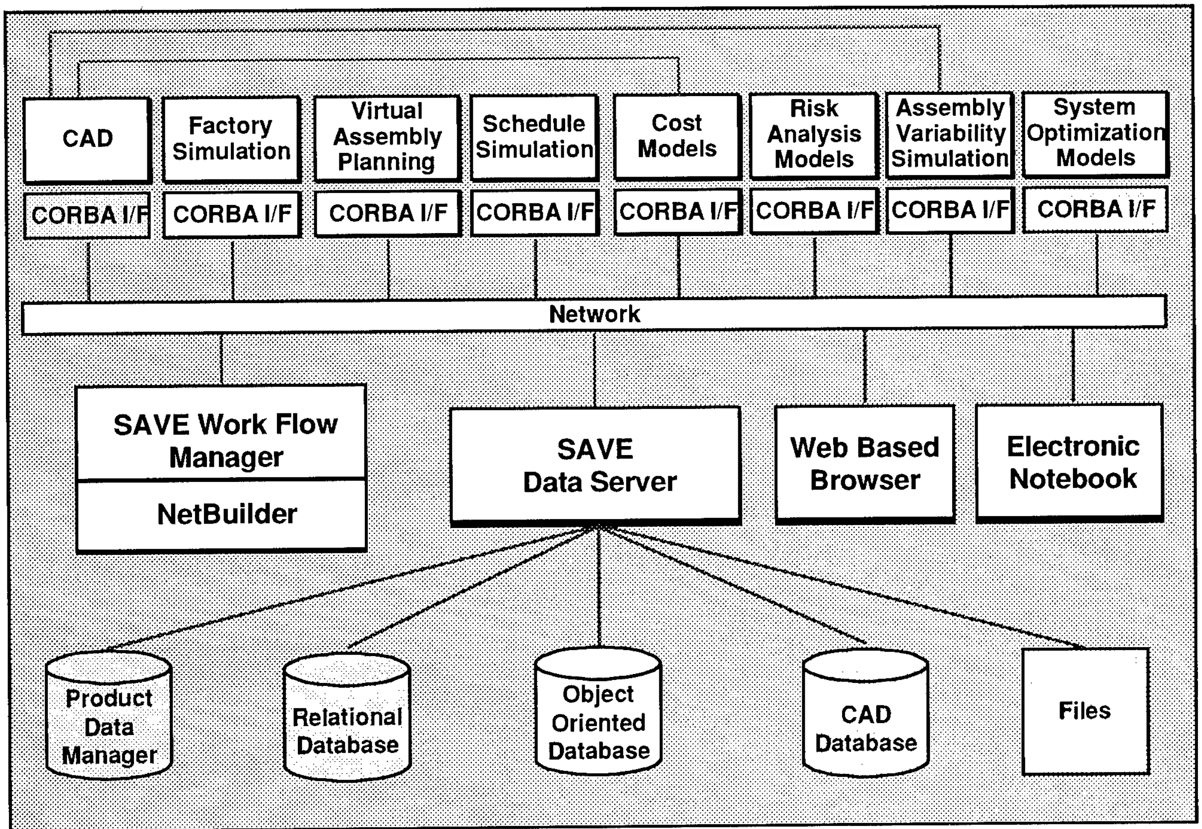

Figure 2. CORBA Approach To Tool Integration

manufacturing simulation classes but is not dependent on the particular commercial tools chosen for use on the contracted effort. While the SAVE team considers the particular tools selected for the contract, Figure 3, to be best of class, other tools can be substituted and new classes of simulation codes (within the manufacturing simulation domain) can be added by simply wrapping the code with a SAVE compliant interface to the infrastructure and data model server. SAVE Architecture and I/O Specification documents have been released into the public domain and are available by request from the JSF program office or from Lockheed Martin.

TOOL CATEGORY	VENDOR	TOOL NAME
CAD	IBM/Dassault	CATIA
Cost Modeling	Cognition	CostAdvantage
Schedule Simulation	Pritsker	FACTOR/AIM
Assembly Simulation	Deneb Robotics	IGRIP/ERGO
Factory Simulation	Deneb Robotics	QUEST
Risk Assessment	SAIC	ASURE
Assy Variation Sim	VSA	
System Optimization	DDI	Production Simulation

Figure 3. SAVE's Demonstration Tool Set

The CORBA standard for distributed interoperable object computing was selected to simplify running a SAVE system on a distributed, heterogeneous computing network. An object-based SAVE Data Server, built using CORBA, effectively isolates the individual simulation codes from having to deal with the actual data storage systems, which will likely be different for each SAVE implementation.

For the SAVE contract demonstrations, data objects will be stored in a single object-oriented database. The SAVE architecture, however, flexibly allows data elements to be stored in several locations, as required by an implementation site, to eliminate problems of data redundancy.

The two lines at the top of Figure 2, linking CAD to the Cost Models and Assembly Variability Simulation represent tight code to code links which interactively extract CAD feature data for cost and tolerance analysis. While SAVE is developing one such link (between Dassault's CATIA and Cognition Corporation's CostAdvantage), links between other tools are already commercially available and are not a limit on SAVE's flexibility.

The SAVE Data Model manages the data which must be shared among the set of virtual manufacturing simulations. It is important to note that SAVE is not attempting to manage all data used by all tools, but is focused on interfacing the data which can be shared among the tools. Geometry data, typically contained in a CAD database , is not contained within the SAVE data model. This philosophy reduces the scope of the SAVE effort while accomplishing the goal of making the full set of tools affordable to apply to design studies.

Figure 4 shows a representative set of data which can be shared among the tools. While this list is not all inclusive it does illustrate the wide range of data and the extensive reuse that typifies the virtual manufacturing simulation problem domain. The SAVE Data Model defines, in detail, data objects and attributes which cover this domain and provide efficient simulation code interfacing. Data are entered once, and used many times, without manual data reformatting and reentry. The SAVE Data Model is extensively documented in both graphical and CORBA Interface Definition Language (IDL) formats in the SAVE Tool I/O Specification, Release 2.0.

4.2 SAVE Infrastructure

The SAVE architecture provides a set of infrastructure tools to aid Integrated Product/Process Teams with the operation of the SAVE integrated tools in an organized manner. This infrastructure, referred to as the SAVE Design Environment (SDE) is illustrated in Figure 5. SAVE will implement a flexible open architecture allowing new tools to be easily plugged into the overall system. The categories of tools being integrated under the current SAVE effort are clearly shown.

These tools are supported by capabilities shown in the horizontal boxes in Figure 5, including :

- Common desktop user interface
- Manual code launch
- Automated work flow management
- Distributed electronic design notebook
- Data model browser for access and reuse

The SAVE infrastructure also contains low level elements supporting communications and data repository management.

Elements of the SAVE infrastructure are implemented as distributed CORBA objects to provide a flexible, expandable system which operates in a distributed heterogeneous computing environment. Integrating a new virtual manufacturing code to operate within SAVE involves wrapping for infrastructure support and wrapping for data integration. Approximately 40 person hours are required to interface with the infrastructure. Effort to interface with the object-oriented data model varies with the amount of input/output required, but is estimated to require 200-300 person hours.

Note : This list is not all inclusive	CAD	Factory Simulation	Assembly Planning	Schedule Simulation	Risk Analysis	Cost Analysis	Variation Analysis	Enterprise Optimization
Process Plan / Work Inst		●	●	●	●	●	●	●
Geometric Models / Defn	●		●		●	●	●	
Task Durations		●	●			●		
Resource Estimates		●		●				●
Rates and Factors		●	●	●	●	●		
Process Rates		●	●					
Factory Layout / Definition	●	●		●				
Manufacturing Rules				●		●		●
Timelines				●				●
Feature Definitions	●					●	●	
Cost					●	●		
Tolerance Limits					●		●	●
Risk					●		●	●

Figure 4. Examples of SAVE Common Data

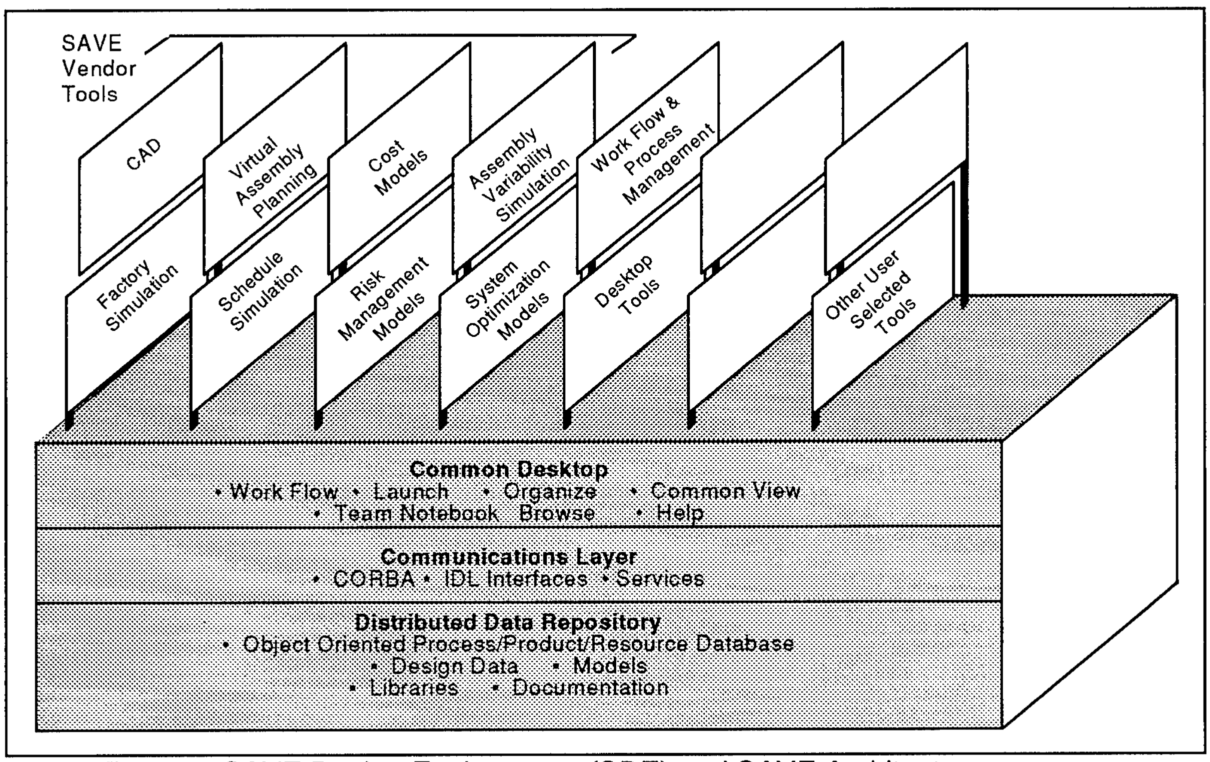

Figure 5. SAVE Design Environment (SDE) and SAVE Architecture

4.3 Feature Based Cost Models

The SAVE Cost Modeling System, built on the Cognition Corporation's Cost Advantage product, is comprised of a series of knowledge bases that are used to define cost and producibility rules for manufacturing processes based on information about product features. SAVE is developing four cost models, which will be validated in demonstrations and delivered to Cognition for commercialization. Site specific data are stored in external tables allowing easy implementation and customization.

These cost models include :

1. 5-Axis machined parts
2. Hand lay-up composite parts
3. Sheet metal
4. Assembly cost model

Each of these models rely on the CAD feature extraction capabilities provided by the CAD to cost model CostLink shown in Figure 2 and discussed above. Typical inputs and outputs associated with the four SAVE cost models are shown in Figure 6.

Cost Inputs	Cost Outputs
Feature Parameters	Recurring Mfg Labor Cost
Material Selection	Recurring Material Cost
Process Selection	Non-recurring Tool Mfg Cost
Number or Units	Non-recurring Tool Mtrl Cost
Units per Aircraft	Non-recurring Engineering Cost
Weight	First Unit Cost
Programmatics	Sustaining Tool Eng Cost
Other	Sustaining Tool Mfg Cost
	Quality Assurance Cost
	Process Plan Simulation

Figure 6. Typical Cost Model Data

Figure 7 illustrates the process of building feature based, process oriented cost models. These models contain both logic and equations to properly relate features to parts and processes. Costs are estimated in a naturally decomposed manner and producibility rules and guidelines may be checked to provide near real time feedback to designers.

5. SAVE PROGRAM PLAN

5.1 Overall Plan

SAVE is being developed in two phases. Major elements of the program plan are illustrated in Figure 8. During Phase 1, completed in December 1996, the SAVE team developed the overall Concept of Operations for the SAVE tool set. This initial concept of how to apply virtual manufacturing simulation tools provided the base requirements for both the infrastructure and tool integration approaches and provided the basis for the Initial demonstration, which is discussed below.

During Phase 2 the SAVE system will be refined in both implementation and validation, leading to a system ready for initial production use and commercialization. Phase 2 contains two cycles, each of which enhances the efforts of the previous phase and leads to a more comprehensive demonstration. Both the Interim and Final demonstrations will involve application of SAVE to on-going F-22 design activities. Formal beta testing, at two JSF weapon system contractor sites, will begin immediately following the Interim demonstration in June 1998.

During each cycle, the concept of operations will be updated based on the latest experience with the SAVE system. The published Concept of Operations document provides an excellent starting point for organizations beginning SAVE implementations, and is available through the JSF program office. While the documented operational concepts provide a successful approach to the use of virtual manufacturing tools, the SAVE system does not rigidly implement one approach.

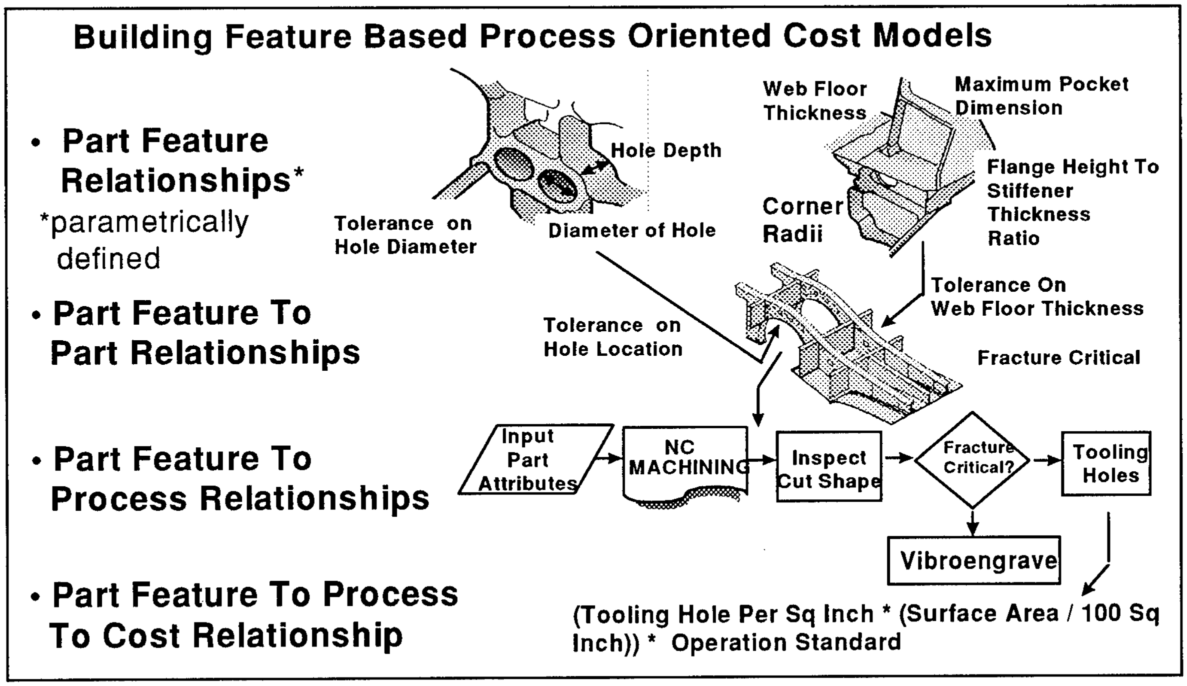

Figure 7. SAVE Cost Methods Overview

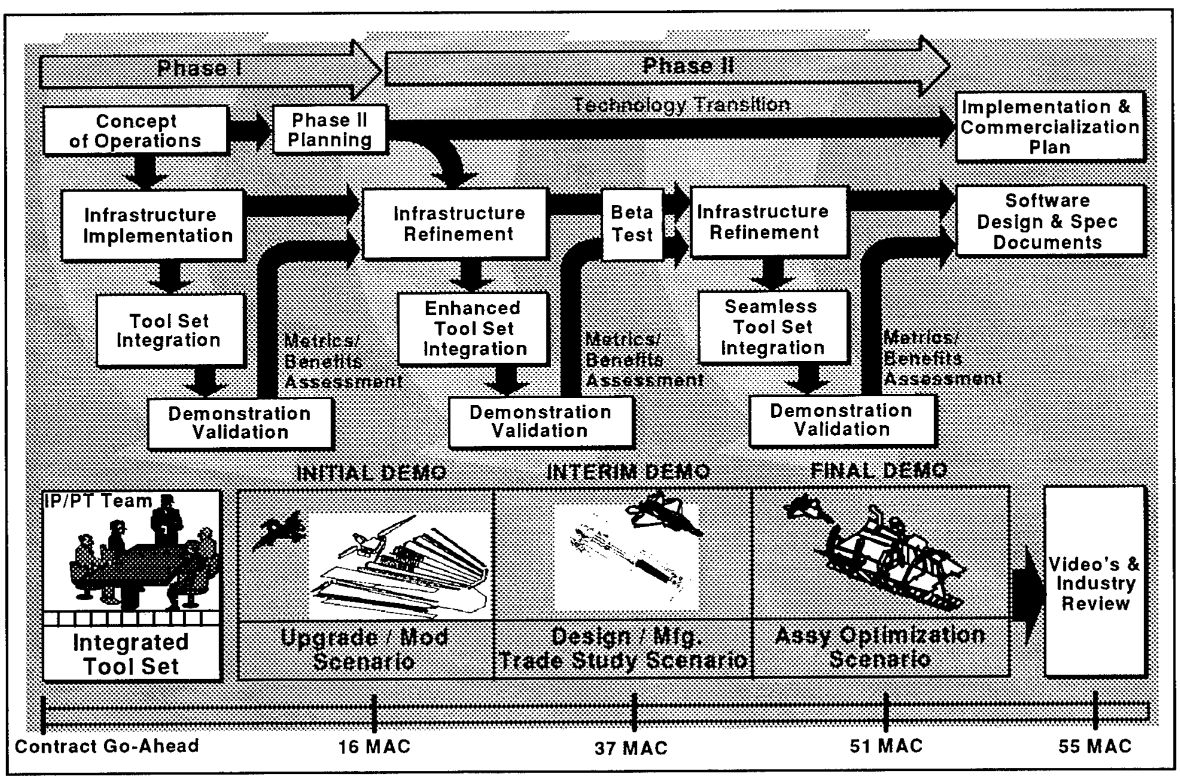

Figure 8. SAVE Program Plan

SAVE allows IPPTs to flexibly determine the process to be used for each design study. IPPTs will map their desired process into the work flow manager, which will support, but not constrain, the team.

SAVE infrastructure and tool integration will be refined in two cycles in Phase 2. During the Interim cycle, SAVE will reflect the eventual production approach, but will be somewhat limited to the demonstration and beta test requirements. In the Final cycle, SAVE will be extended and enhanced based on both Interim demonstration and beta test experiences.

Major deliverables from SAVE include the software specification and design documents and an Implementation and Commercialization Plan, briefly described below.

5.2 SAVE Demonstrations

The SAVE program includes three major demonstrations, illustrated in Figure 9 and discussed below.

The objective of the Phase 1 demonstration was to validate that a set of disparate commercial off-the-shelf simulation tools could be seamlessly integrated and that this integrated set of tools would produce results that closely correlate to manufacturing actuals from a real world production program. The component selected for this validation was the F-16 horizontal stabilizer. This component was selected for three reasons: 1. The stabilizer structure was dramatically changed during the redesign; 2. The change made to the stabilizer was isolated from most other manufacturing activities so that the data collected from historic files could be easily isolated for direct correlation to the simulated data; and 3. The F-16 program provides an extensive data base that could be used to analyze the simulation results. SAVE simulation estimates of cost, schedule, and risk correlated well with actuals; cost was within 15%, schedule was within 18%, and risk was within 3% of F-16 program data. SAVE was successfully used on the Initial demonstration and measurable progress was made on each of the program metrics.

The Phase 2 Interim demonstration will apply SAVE to a typical design / manufacturing trade study scenario, the redesign of the F-22 gun port. Design changes are required for performance reasons, but affordability will continue to be a design driver. A major criterion for selection of the gun port redesign was to apply SAVE to an on-gong design activity thus increasing the reality of the demonstration, providing eventual actual data for the metrics, and to begin the implementation of SAVE on the F-22 program.

In the final demonstration SAVE will be applied to a major assembly optimization scenario utilizing the F-22 forward fuselage. This demonstration will apply the final contract version of the SAVE system and is planned to validate a large percentage of the estimated affordability metrics, listed in Figure 2.

5.3 Beta Testing

The current SAVE program plan provides for formal beta testing of the SAVE system as it exists in mid 1998. Desire for beta testing was voiced by representatives of SAVE's potential users and by the commercial software vendors. Both groups believe that this testing is necessary to more rapidly mature the SAVE software and to address the difficult cultural issues of real production implementations.

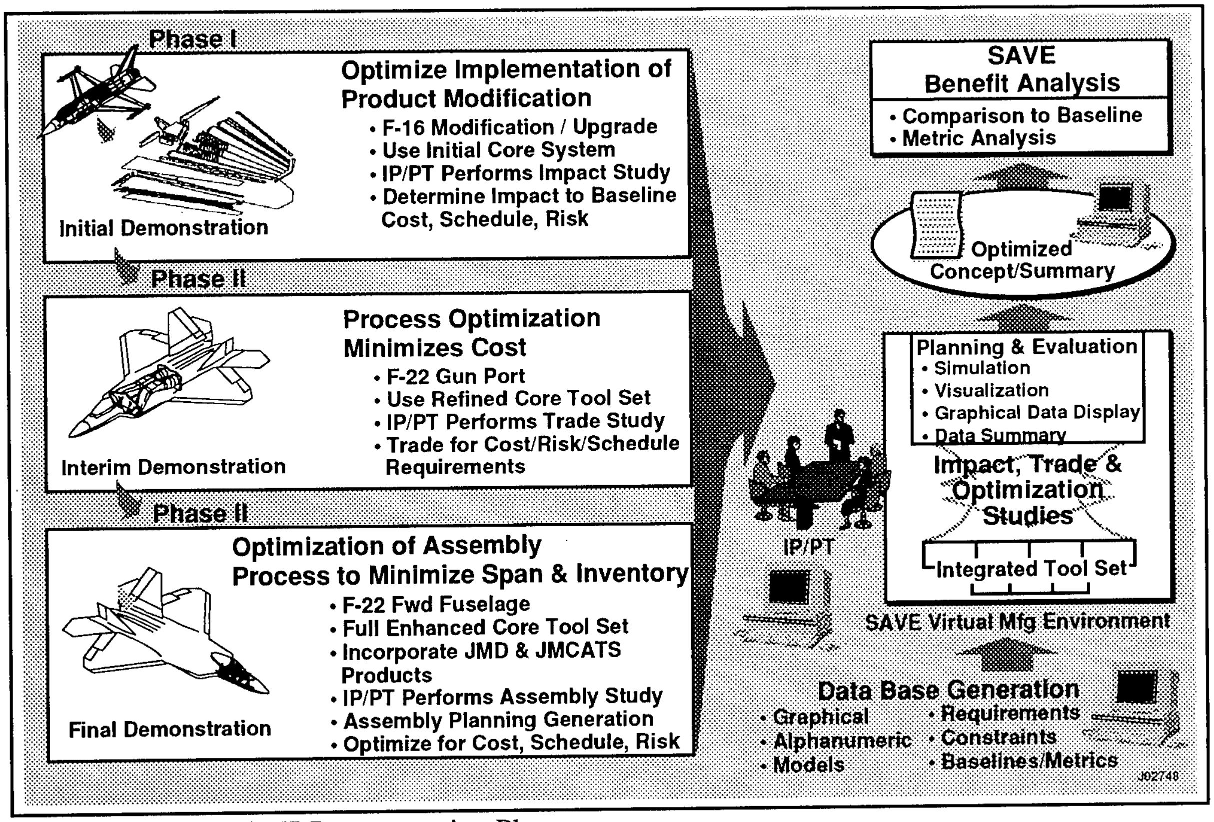

Figure 9. SAVE Demonstration Plan

Two beta test sites will be selected and will participate in determining SAVE functionality needed for testing. Beta tests will be scoped to run for approximately 3 months and will include the broad Interim demonstration capability and more complete functionality with a limited set of simulation codes. Metrics will be measured during these test problems and results will be reported in SAVE program reports.

5.4 Implementation and Commercialization Planning

The SAVE program is not intended to produce a complete production implementation of the capability described here. The SAVE team will :

1. Produce a viable approach to an integrated virtual manufacturing system
2. Validate that approach through realistic demonstrations
3. Validate the basic premise that virtual manufacturing simulations will achieve significant affordability benefits
4. Develop plans to make a SAVE system commercially available in time to support the JSF Engineering Manufacturing Development program
5. Develop implementation plans to aid prospective users in rapidly bringing SAVE to productive use

Initial version of the Implementation and Commercialization Plan will be available in June 1998 to support user site implementation decisions following the formal beta tests. Commercialization planning is in preliminary

stages, with encouraging response from both prospective vendors and users.

5.5 SAVE Software Design Specification Documents

SAVE is designed as an open system and its design specifications will be made widely available during the contract as well as in final delivered form. This will maximize the overview and input from prospective users, commercial software vendors, and standards development activities. Phase 2 working level design documents are available now, and will be continually refined as the program progresses. Requests for this documentation should be made to the SAVE Program Manager at the address show on the title page of this paper.

6. SAVE PROGRAM SCHEDULE

A top level program schedule for SAVE is shown in Figure 10. SAVE is currently in the design stage for Phase 2, Interim cycle. New versions of the SAVE design documents have been released including the Concept of Operations, Architecture, Tool Integration, and Interim Demonstration Description. The SAVE infrastructure, data server software, and tool wrappers are in initial stages of coding. The two JSF prime contractors, Lockheed Martin and Boeing, have been selected as the beta test sites, and initial beta test planning is underway to define the test problems and the required SAVE functionality.

The Interim SAVE system will be complete in early 1998 and will be used in the Interim demonstration scenario. Formal presentation of the demonstration is scheduled for June 1998. Beta testing will be conducted at the two sites beginning in late June 1998. Final cycle software development will be accomplished in the last half of 1998, supporting the final demonstration scenario in early 1999. The formal presentation of the final demonstration is scheduled for July 1999. All SAVE program documents will be released in final form in late 1999.

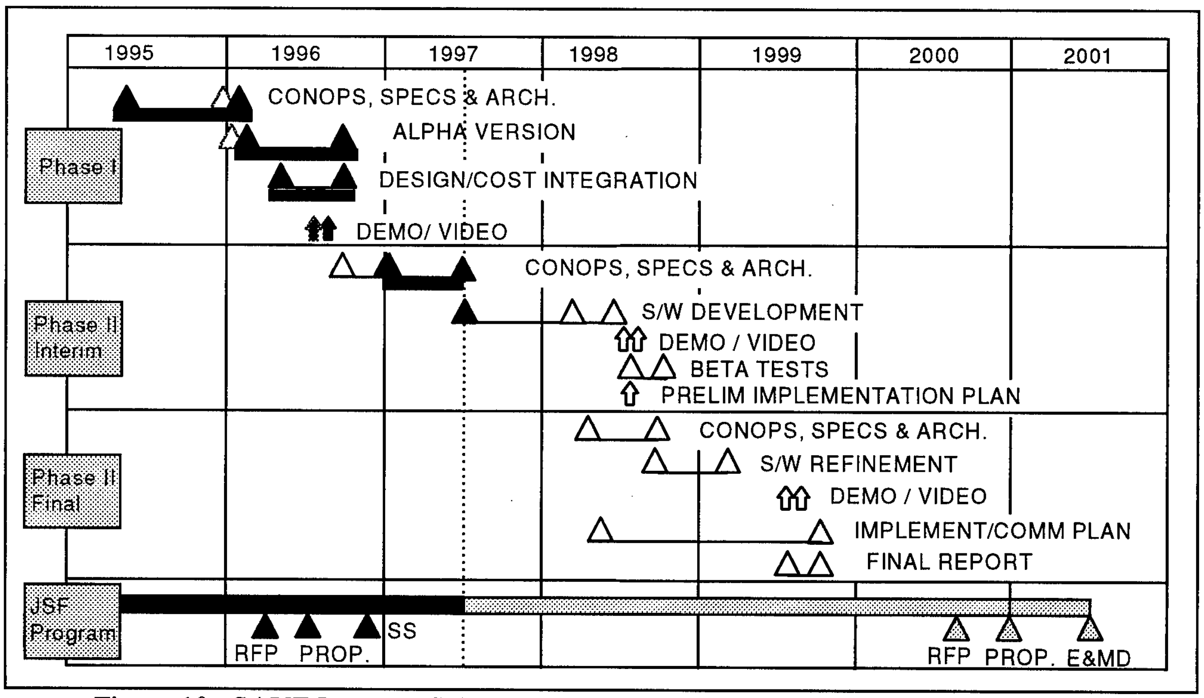

Figure 10. SAVE Program Schedule

Implementation of Airbus Concurrent Engineering

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Abstract

In the 27 years since it was founded, Airbus Industrie has developed a portfolio of aircraft in the above 100 seat range which has captured over 35% of the global market. This has been achieved despite the the fact that, up to 1995, the Airbus partners used a variety of software systems.
However,at the end of 1995, the fourAirbus partners signed an historic contract, commiting the partnership to buying at least 1500 seats of common CAD/CAM/CAE and enterprise data management software from a common supplier - Computervision.
Airbus realised that its aggresive competitive goals could only be reached if all partners adopt common ways of working across Europe. To drive this change,it launched an Airbus Concurrent Engineering (ACE) project in 1996 to enable it to revolutionise the way it designs, builds and supports aircraft .
This paper will describe the work in British Aerospace to produce a radical vision of world class people, processes, systems, teamworking and performance. It will illustrate how this vision was developed and shared by the Airbus partnership, resulting in a strategic plan to provide a revolutionary change in performance, enabling Airbus Industrie to proceed towards its goal of being a leading aircraft manufacturer in the world.
It will show that ACE is "not just another IT programme" but a change programme delivering hardware, software, networks, processes, tools, methodologies, organisation, training and support - in a contract with Airbus aircraft programmes called a "version"
The pivotal role that the ACE project plays was reinforced by the Airbus partners signing a memorandum of understanding with the intention to establish a single Airbus company by 1999.

1. INTRODUCTION

Airbus Industrie has a vision which shows it capturing 50% of the above 100 seater aircraft market by early next century.

It plans to achieve this goal by not only continuing to offer the most technically advanced aircraft in the world but also by meeting the following goals, with respect to the baseline performance achieved on the A340 aircraft:

a) Lead times cut by 50%
b) Resources cut by 50% for similar tasks
c) Product quality increased.
d) Manufacturing costs cut by 30%
e) World leading levels of customer satisfaction
f) Maintenance costs reduced by 30%

How could this be done within a consortium which spans four countries, four cultures and has a diversity of computer systems?

It was clear that the driving force for the change could only come from a combined decision to throw away the baggage of the past and to reach a consensus on the opportunities available through the introduction of common systems across the whole partnership, *with its products defined by a single, common enterprise data management system.*

This paper describes the events leading to the historic decision by the Airbus partnership to use such common tools and also describes the swift progress made after the consequent agreement to collaborate on the development and implementation of common processes and teamworking to fully exploit such systems.

The decision to establish a single Airbus Corporation by the end of 1999 has only served to reinforce the motivation and effort of the teams and individuals working towards these radical changes.

2. WHERE DID WE START?

During 1995, all partners were working on various, loosely connected change programmes. The objectives, principles and methodologies had many similarities, eg all had a

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process orientated approach, and all had a common view of world class/world beating targets.

Because of these similarities, as an illustration of the general progress, approach and learning points, the British Aerospace Airbus project will be described, before considering the genesis of the joint Airbus Concurrent Engineering (ACE) project.

The objectives of the British Aerospace project were based on consideration of the following questions:

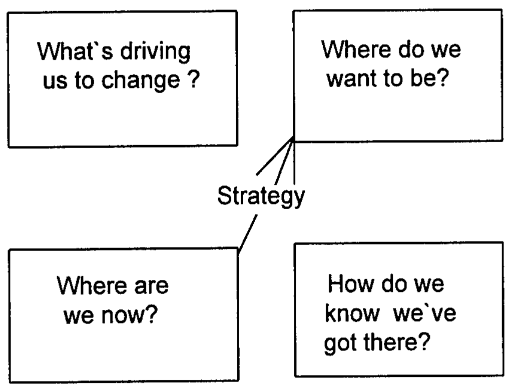

Figure 1: A system view of change - the vital questions

a) What is driving us to change?
   - *market, financial and competitive imperatives*

b) Where are we now?
   - *people, processes, systems and data.*

c) Where do we want to be?
   - *the 5 and 10 year vision*

d) How do we get there ?
   - *the strategy*

e) How do we know we're there?
   - *performance measures, metrics*

It was clear that the company had to change quickly; to meet the financial targets set by its shareholders, to challenge and exceed the goals of its competitors and to meet the needs of its customers.

The analyses of the current position revealed a company which was the technological world leader in the production of wings, but was suffering from pain inflicted by a functional, serial "over the wall to you" design and manufacturing process, supported by functional, in house computing systems with business and product data spread throughout the company.

The senior management reacted quickly - producing their vision of the company in the year 2000. The principal elements were:

a) Process orientated working

b) Team based, multi disciplined organisation

c) Valued and flexible people

d) A flatter, empowered organisation

e) Integrated, commercial systems and tools

f) Worlds best wing producer

g) Focussed on customer needs

h) Profitable

i) Enjoyable!

The strategy required to reach this vision was in four parts:

1. To gain management commitment to the vision, to test it and amend it through workshops involving the whole company.

2. To introduce a process led way of working for projects through the establishment of Design / Build / Procurement teams, working in a concurrent engineering environment.

3. To test the concept in practical pilots and to apply it quickly to real aircraft work.

4. To involve the whole workforce in a programme to facilitate "quick hits" - looking for any local improvements and applying them immediately, so that everyone has a sense that things are moving in the company.

Learning Points

1. It is only through the emphasis on business and market drivers that the whole companys commitment to change is made - it is too painful to stay where we are- we have to change.

2. To gain commitment, it is essential to counteract any concern caused by this pain by emphasising and presenting the opportunities to change through benchmarking and best practice examples - this is what the worlds best are doing; we can go beyond it.

3. The vision workshops were an ideal approach to gain commitment - every person in the company was involved and had an opportunity to challenge the vision. It was still owned by the directors , yet at the end of the workshops many vision themes had been amended for the better.

4. Somethings happening!! Set up a simple system to capture, publicise and implement quick hits.

5. Use a standard simple framework to describe current and desired process performance. British Aerospace used some basic IDEF modelling, together with some effective metrics for each process.

> Choose a past project or task.

> Set up a diagnostic team consisting of people who worked on that project

> Establish resource used and time taken.

> For each process, calculate value added vs non value added resource.

> For non value added, use cost of quality definitions to categorise the resource:

* ***Prevention***- *preplanning-ok* *(The GOOD)*
* ***Appraisal*** - *checking- ok if only that which is necessary to confirm the process output* *(The BAD)*
* ***Failure*** - *rework, scrap - not wanted at all* *(The UGLY)*

> Use a why-why analysis to get to the root causes of the non value added elements

> Publicise to all existing projects, apply as learning points to the planning phase of similar new projects.

6. Don't get enmeshed in huge IDEF and computer simulation analyses. Use simple frameworks that suit your company and that everyone can understand; the cost of quality approach, a Burke Litwin framework for vision generation, Quality Function Deployment techniques to capture customer wants, etc

3. WHAT ABOUT IT!

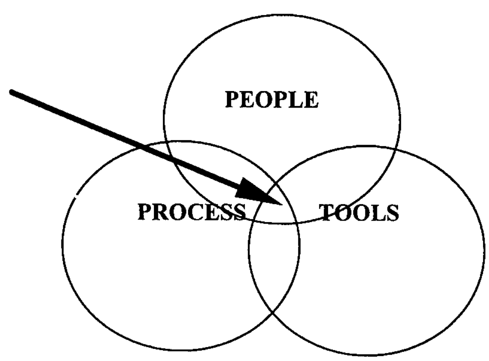

Figure 2: People, Process and Tools - essentials for a concurrent engineering approach

This figure attempts to illustrate a system approach to concurrent engineering. A number of companies have obtained a measure of benefit by adopting change based on an approach which concentrates on pairs of the above elements:

PROCESS/TOOLS
Benefits achieved by automation of processes.

PEOPLE/TOOLS
Benefits achieved through sharing of information in databases.

PEOPLE/PROCESSES
Benefits achieved through the establishment of new ways of working

However, common sense and case studies show that the fullest benefits can only be achieved if a PEOPLE/PROCESS/TOOLS approach is used - a Concurrent Engineering approach.

It was clear that the British Aerospace Airbus approach at the time had been based on the PEOPLE/PROCESS axis - setting up design build teams to define new ways of working, but using existing tools and systems.

4. WHAT SYSTEMS DO WE NEED AND WHERE ARE THE AIRBUS INDUSTRIE PARTNERS?

During 1995 British Aerospace Airbus had started to evaluate the replacement of existing CAD, CAM, CAE and product data management systems.

Reviews of existing systems revealed the following concerns:

> The new processes
> The attributes of any system to support these processes
> The definitions of best practice
> The demonstrations of benefit
> The assessments of risk.

The approach was based on a Quality Function Deployment technique. It is described, later in this paper, in terms of a flow of activities giving an output consisting of a ranking of five major CAD / CAM / CAE / data management systems in terms of their support to British Aerospace and Airbus Industrie processes, teams and aircraft programme and business goals.

Yes! also the Airbus partners. At this time (late '94), it was clear that the three major partners in the consortium were looking at replacement IT systems. Their current major systems included:

British Aerospace - Anvil, some CATIA, some Unigraphics
Aerospatiale - CADDS4X, some CATIA
Daimler Benz Aerospace - CADAM, some CATIA

An historic opportunity beckoned for the partnership and it was to the credit of three major partner directors: Ray Wilson, Gerd Eisen and Gerard Blanc, that they not only agreed to collaborate on a choice but also to directly sponsor the work.

Various, but similar, approaches to the evaluation were made at the three companies. The British Aerospace flow of activities, described below was based on a Quality Function deployment approach:

1. Consider the project scope as the whole of British Aerospace, its partners, suppliers, subcontractors and customers - the "extended enterprise".

2. Consider the applicability to be all project phases from concept, through design, manufacturing, in-service support to product retirement.

3. Apply to existing, modified, derivative, new and future aircraft.

4. For each area of application, set up a task team to define and rank the processes undertaken as one axis of a matrix. .

5. Along the other axis define the technical attributes required of any system to enable the required output of the processes to be achieved. Rank the attributes in terms of criticality to the output.

6. Challenge the process definition and ranking vigorously, provide examples of best practice for companies, not only in aerospace, but wherever they may be found.

7. Visit vendors, visit companies which use vendor products (*unaccompanied* by vendors), visit any company which exhibits best practice. Ensure your team is representative of the enterprise and that they can make direct contact with their peers at any company visited. Record visits on a suitable benchmarking framework related to the QFD matrices.

8. Write test scripts for the competing systems, evaluating in particular, critical attributes versus most important processes.

9. Score each system against:

> Current internal system scores
> Scores related to observed "Best in Class" attributes

The process established CATIA from Dassault Systemes and CADDS5 from Computervision as short listed products for the final intense evaluation in which the three major Airbus partners collaborated.

Without revealing the scores, it was clear that the big differentiator in favour of the winning product was its integrated data management system, together with a strategic roadmap for the product, specifically leading to a vision of a "best in class" enterprise data management capability

In June 1995, the partners agreed unanimously to choose Computervision and the framework contract was signed by the three partners in July, 1995 with the local contracts signed in late September. This was the largest contract obtained in the history of Computervision.

Learning Points

1. Involve the whole enterprise - it is then "our" solution, not an imposed solution from Airbus or British Aerospace or IT or senior management, etc.

2. Use a structured approach eg QFD, and base it on what the competing system can provide NOW not what their salesmen promise for a year hence.

3. Conduct assessments, linked to the QFD matrix, of the current development activities at the vendors and establish the strategic intent behind their "road map" for their product.

4. Do not allow vendors to take you on tourist visits around their successful installations. Arrange the visits directly with the companies, take a large, representative team (we used 20-22 people) and ensure that they can talk, unsupervised, directly to their peers.

5. Install equipment from the shortlisted vendors on your site, make every effort to ensure that all areas of the company perform their QFD analyses and test scripts using the vendor equipment personally.

6. Don't just look at your competitors and your industry, seek out best practice wherever it can be found.

7. Have a strong sponsor team with direct, short links to the evaluation team.

8. Welcome benchmarking visits from other companies. You've done it to them!

5. WHAT NEXT?

The partner Sponsor Team recognised that common goals could not be achieved just through collaboration on common tools. Therefore, in July 1995, they set up an Airbus Concurrent Engineering (ACE) project with the following vision:

To develop and progressively implement Concurrent Engineering processes and methodologies across the Airbus partnership by the year 2000

The project team (ACE Core Team) consisted of the Implementation project leader from the three partners plus a change programme leader from each partner, including participants from Airbus Industrie.

With the decision of the fourth Airbus partner, CASA of Spain, to join the ACE project, the project now includes all of the partners in Airbus Industrie..

6. WHAT IS THE ACE PROCESS?

The **domain of the project** was defined as the areas of process improvement associated with the whole life cycle of an aircraft programme; from feasibility through to aircraft retirement.

The **deliverables** would cover both new aircraft and derivatives of current aircraft.

The **applicability** would be for Airbus collaborative and, as a desirable target, internal partner projects (eg collaborative projects outside the Airbus partnership)

The **process participants** would come from the Airbus extended enterprise, covering all disciplines and functions within the partners, together with customers, suppliers and subcontractors. (Note that this relationship has been considered within the partner contract with CV, where partners can allocate software licences freely to their suppliers, sub contractors and new partners.)

The **customers for the deliverables** would be the project directors of Airbus and single company aircraft programmes - there is no deliverable unless the substance and benefits are bought by the customer.

The **areas of work** were defined in four, interrelated groups, containing some 28 defined areas. Teams were, however, only launched where there was perceived to be the potential for significant benefits on forthcoming aircraft programmes. This focus resulted in the launching of 9 teams (plus one sub-team) for the first ACE phase:

> ***Business Process teams***

Business processes were defined as the top level processes which were common across the partnership, grouped into separate sets, with a specific output *defined by a customer*. Five such processes were identified and two teams were l aunched:

a) Design Integration & Build
b) Order Fulfilment

> ***Technical Process teams***

Technical processes were those activities which occur in all business processes but which can be grouped as a recognisable set ofactivities, eg processes concerning Electrics, Piping, Surfaces, etc. These are sometimes called *industrial processes*. Seven such processes were agreed and three teams and one "sub process" team were mobilised:

a) Surfaces
b) Electrics
c) Structures
d) Stress (sub-process of Structure)

> ***Cross Section teams***

Cross section tasks , *not processes*, were those tasks which affected all processes and areas of work. Examples were Configuration Management, Quality Assurance, Aircraft Certification. Of the seven groups of tasks which were identified, two teams were launched:

a) Configuration Management
b) Data Management

The remit of the Data Management team was to develop a definition of the future ACE (Airbus) information model, and also to provide proposals for the strategic path towards such a model, covering data organisation and models for pilot implementations and early aircraft programme implementations.

> ***Tools teams***

These teams were already established as the single points of contact for the vendor, Computervision, CV, with respect to the contractural agreement for CV to fill the gaps between their product and best in class, as defined by the partnership and agreed by the vendor.

It was clear that the tools teams had to act as cross section teams, gathering tool requirements, providing current tool capabilities and revising the CV product development plans as new and revised tool requirements were defined via the common to-be processes. The two teams were:

a) CADDS5 tools team
b) Optegra (CV data & config mgt modules) tools team.

The **organisation and management** of the tasks for the first phase was carried out by the ACE Core Team, using a *goal directed project management* approach in conjunction with the teams and their Team Leaders.

The **integration and coordination** of all the team outputs was done by a Process Integration Group. This group was also responsible for ensuring that the team work followed the *common methodologies and guidelines* agreed between the ACE Core Team and the Team Leaders

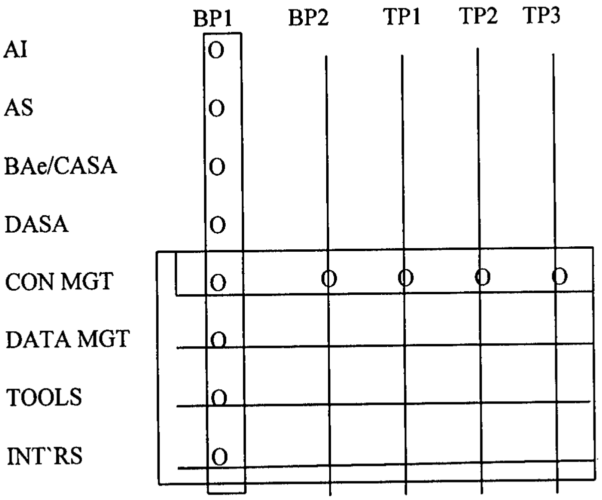

Figure 3: Organisation of ACE teams

Legend

TP - Technical process　　BP - Business process
AI - Airbus Industrie　　AS- Aerospatiale
BAe British Aerospace　　DASA - Daimler Benz
CASA- CASA,Spain

This figure shows that each technical and business process team includes members from each partner company, but also includes representatives from both the Cross Section teams and the Process Integrators, ensuring that all issues with other teams/processes can be captured immediately. It also enables the cross section teams to test their vision and proposed policies and rules with all other teams

7. ACE PHASE 1 DELIVERABLES

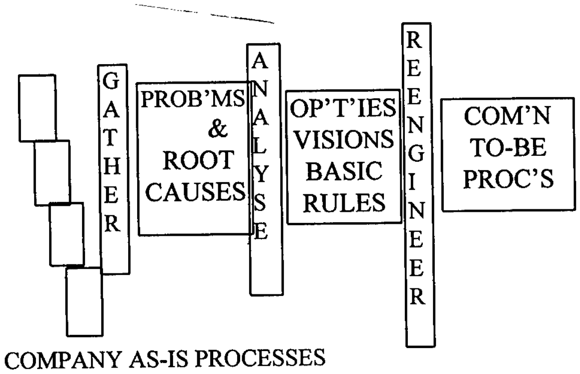

Figure 4: Basic elements of the ACE Phase 1 methodology

This basic methodology was agreed as the focus for the ACE teams for the first four months of the project; March to July, 1996.

> **As-Is Processes**
A quick exercise gathering together existing partner company information describing their as-is processes; coordinating the information and recording it using the IDEF0 format. Further work involving deep analysis was only attempted in areas where it was clear that a major problem (ie major opportunity for benefit) existed.

> **Problems and Root Causes**
Brainstorming exercises were held in each team and the results were stored collectively in a database, together with an analysis of the problems in terms of their *negative* impact on the individual partners, the Airbus partnership and the customer.
These impact metrics covered time, cost, quality and resource, allowing major problems to be selected quantitatively. To gain an idea of the root causes of the major problems, simple why-why exercises were used at this stage.

> **Opportunities**
Opportunities were held in the same database as the problems and were largely expressed as *solutions* to the identified major problems.
Also as measures of *improvements/benefits* for domestic partners, the Airbus partnership and for the customers.

> **Vision and Basic Rules**
This was a fundamentaly important exercise for Sponsor Team and was used by each team to consider in detail:

a) What the "local vision"was for their domain
b) What were the basic rules or guiding principals
c) What was the view of "stretch"

> **Common To-Be Processes**
Using a common view of aircraft programme milestones and a common view of the deliverables expected by the customers at these milestones, the teams took a radical view of the to-be processes.
Understanding the problems/opportunities and potential differences (benefits) ,with reference to the as-is processes, allowed the final workshop to decide that *the Sponsor Team targets were achievable for both new and derivative aircraft programmes.*

The ACE project has a joint agreement on deliverables across all teams, together with a common set of information:

1. The as-is processes in IDEF0 notation.
2. The to-be processes in IDEF0 notation.
3. The process milestones in agreed notation.
4. The differences to the old process.
5. The projected benefits from new process with respect to the Sponsor targets.
6. The basic rules/guiding principles to govern the new processes/ways of working.
7. The vision of people, process, technology and data for the future aircraft programmes.
8. The links and dependencies between processes.
9. The dependencies and requirements related to the tool development programmes.
10. A first view of potential aircraft programme pilots.
11. A view of the new/amended areas for teams to address in the next phase of the ACE project.

8. OUTPUTS OF ACE PHASE 1

Two significant pieces of work were achieved during phase 1: a) establishing of a set of generic aircraft milestones which cover the the lifecycle of an aircraft project, b) the set of information objects which are created and delivered by the project during its life. These outputs have now been used as the basis of a planning exercise to establish the content and timescales of the ACE versions to be delivered to the business and used by the aircraft programmes.

Generic aircraft milestones

From the 'as is' process work the ACE team established that there were 14 milestones and that they denoted key points in the life cycle of a project. These key points are used as decision or check points on wether to move onto the next phase of programme or not.

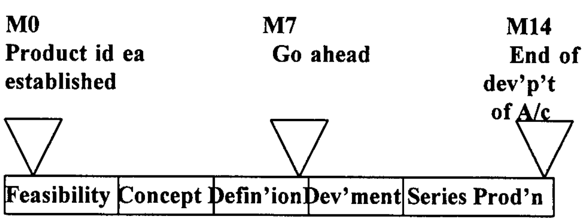

Figure 5: ACE Milestones

These milestones have been broken down into sub levels which become detailed tasks and events i.e. Geometry frozen and Wind tunnel tests received. These sub-level tasks can then be used during the planning phase of an Aircraft programme.

Information Objects

The second piece of work was to establish the 26 information objects which are created or collected during the aircraft programme. These objects can be in various forms such as Electronic models, Databases or just Collections of Documents, and are the total definition, certification and support information of the Aircraft. They are stored electronically creating what we call the Electronic Product Defintion.

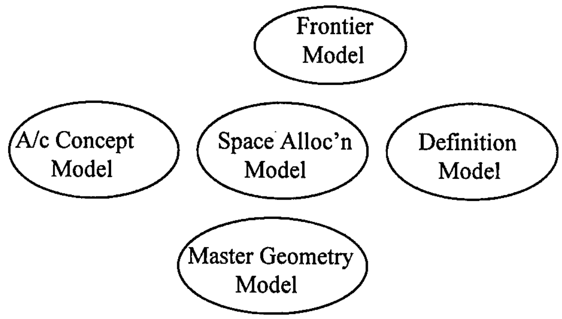

Figure 6: ACE Information Objects

Having established a set of Aircarft data objects created by the programme, we then set about establishing the links between these objects, such as what type of data was contained in the objects i.e. solid models or text, what systems were used to create this information, and which generic milestones would these objects either be created or used. This establishes a lifecycle for each object and an understanding of who was going to create it and use it and when.

Two of the information objects will be described, to give an understanding of their role within a concurrent engineering environment. Both are electronic mock-ups.

Space Allocation Model

The space allocation models are full aircraft mock-ups which represent the structure and systems in a theoretical product and is constructed of simplified solids which demonstrated one or more design proposals. These mock-ups serve as a contract between the design departments of the allocation of space and volume and allow the pre-installation of system routes and mechanisms. All modifications or major evolutions in the design lead to an update of this mock-up which is validated and issued through a design review. The mock-up is available to all engineering disciplines allowing much of the industrialisation process to start earlier

Definition Model

The objective of the definition model is to achieve a higher quality definition of the manufacturing and design data, whilst facilitating a reduction in recurring costs by reducing resources and cycle times during the aircraft definition phase.

This is achieved by using a single source of associated data, which will reduce duplication. The cycle time will be

reduced by making the product data visible and available for a design build team as soon as it is stored in the database. This database is the focus of the concurrent engineering design and manufacturing skills.
This definition model contains the full solid models with its assembly product structure, and the associated attributes on each node. The solid will contain tolerances and be used to simulate assembly and disassembly validation, it will also be hold the differing model states during the manufacturing stages.

From this information and in conjunction with the first Aircraft programme to use the output of ACE , a derivative of the A340, work packages and tasks required to implement the changes to the processes were established, plus the ways of working, the roles of people and tools (computer system) to deliver real benefits for business.

9. THE NEXT PHASE

It is essential to have interaction with aircraft programme customers such that the implemented quickly and have minimal risk by continuously testing and challenging the working methods and outputs of the ACE project, and that the Sponsor goal of " practical pilots on real aircraft programmes" can be met.
Emphasising again that this is "not just an IT programme", the deliverables of the ACE project to aircraft pilot programmes will be in terms of *versions*; not software versions - but issued, agreed standards and guidelines for all elements of a concurrent engineering programme to support a step change in performance:

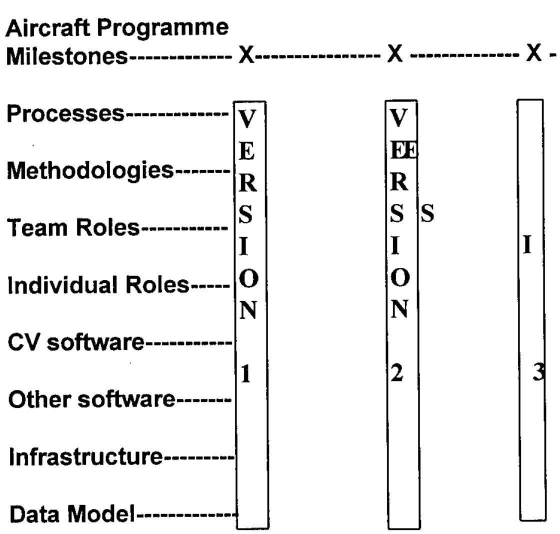

Figure 7: ACE versions for projects

10. ACE VERSIONS 1,2 & 3

The aim of a version is to deliver a capability to the Aircraft project at the appropriate points in its programme, so it will get what it needs when it needs. This splitting of the implementation allows us to deliver company wide concurrent engineering in manageable chunks. Each version will deliver one or more of the information objects as its main capability with supporting functionality, practices and procedures. The first of these versions was implemented in January 1997, with the second in July and the third planned before the end of 1997. The content of these versions and the building of the electronic product definition are described:

ACE Version 1
(deployed February 1997)
As stated earlier the content of a version is aimed at what is required by the Aircraft project during the next phase of its programme, and as our first customer is to be a derivative and in the concept phase. Their initial requirement would be for the following information objects and supporting procedures and practices running on the existing installed Computer Vision software.

The Information Objects for this phase of the programme would be how to create, manage and use **Master Geometry, Space Allocation Model,** and **Frontier Models** these processes would be supported by methods and practices such as **Clash Detection** and **Zone Management,** which includes **Product Structure Tree, Update and Sign-off** , **Naming and Numbering** and a **Change Process.**

ACE Version 2
(Deployed July 1997)
Version 2 was aimed at the definition phase of the programme and required the same basic content as version 1 with extensions to the use of the information objects and a revision of the Computer Vision software.

ACE Version 3
(Due to be deployed December 1997)
The aircraft programme is now completing definition and entering the development (engineering) phase and requires to create a full definition model and data for manufacture, using the latest revision of Computer Vision software.

Therefore Information Objects for this phase of the programme would be how to create, manage and use **Definition Model** with supporting methods and practices of **Detail Part Modelling** including how to use tolerancing, **the use of Standard Parts** and the creation of data for manufacture including minimal content **Drawings.**

11. FUTURE ACE VERSIONS

The next planned versions to be delivered for ACE are in six monthly intervals with Version 4 due in June 1998. These releases will include capabilities and functionality for completing the aircraft process up to in-service support but also for the earlier parts of the programme such as the feasibility phase ready for new aircraft such as the A3XX

The ACE project will reach its current targets when the following milestone is met:

When a full implementation has been achieved which enables aircraft programmes to deliver world class benefits

We will then start again !!

This milestone encapsulates the new approach within the partnership: an implementation programme only exists when it has been agreed with aircraft programmes, and it can be demonstrated that it can achieve the required benefits. This is imperative, not least because such an agreement means that the aircraft programmes accept revised resource levels and project planning milestones based on the world class targets driving the ACE project.

12. CONCLUSIONS

The Airbus Experience describes a project whose time has arrived; the radical change targets are now underpinned by the desire of the partners to set up a single Airbus company in the short term.

The effect on the people in the partner companies has been significant - the "can do" attitude of the people is now augmented by a mindset that identifies their working environment as a leading edge European company, not an Aerospatiale or AI or British Aerospace or DASA or CASA view. They know that the success of the ACE project is imperative for the success of the single company.

We in Airbus know and respect the capabilities of our competitors, but we believe that we have put in train a process capable of enabling the single Airbus Industrie company to become and to remain the best aircraft company in the world.

What are the general lessons that can be drawn from the Airbus experience?

The lessons learned are very simple and direct:

The world won't wait for you to catch up; by the time you catch them they will have already moved on!

Aim beyond best in class, setting **big targets in short timescales**. Don't be dazzled by the technology; anyone can buy it - how you use it, on which processes and with which people is the key - **Process/People/Tools** - supported by properly organised data.

VIRTUAL MANUFACTURING TECHNOLOGY IMPLEMENTATION AT BOEING

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SUMMARY

Virtual Manufacturing is an integrated set of tools and technologies which provide a highly accurate near real time 3D simulation environment to evaluate: new or exiting methods and processes; tool and fixture design/ assembly sequences; facility layouts and material flow; ergonomic/human factors; and alternate production scenarios involving one or more products.

Boeing is expanding its usage of these tools and technologies, as utilization in selected applications has demonstrated dramatic improvements in reducing cycle time and cost, while improving productivity and product quality. This paper will discuss our application of and experience with Virtual Manufacturing for an ever expanding breadth of applications. These include; simulating kinematic devices for Space Station; robotic painting; visualization of airplane assembly processes; and simulation of man/machine interactions, numerically controlled (N.C.) machining cells and composite fabrication processes.

With the successes experienced to date, the authors will look into the next millennium, projecting further advancements in technology and its' projected usage in the aerospace industry.

INTRODUCTION

Major changes in world politics and economics prompt us to examine changes we need to make if we are to continue as an effective aerospace competitor. To win and successfully execute contracts, Boeing Defense and Space Group will need to make major shifts in the way they do business. Mr. Phil Condit, our C.E.O. has stated that in order for Boeing to remain a world leader in aerospace, we must: reduce product cycle times by 50%; and reduce manufacturing costs by 25%.

Toward achieving these goals the factory of tomorrow must exhibit flexibility, reduce cycle time, and decouple cost from volume. It must attain these goals in a business environment which is responsive to our customer's desires, thus is proactive in accepting, validating and implementing change. Without a paradigm shift in the way we do our business, our products will cost too much and take too long to get to market. Vital to attaining these goals is the use of the emerging technology known as Virtual Manufacturing.

By replacing hardware prototypes with computational prototypes, the potential is tremendous for greatly reducing product development times, manufacturing facility ramp-up times, and product development costs. By catching downstream problems early, higher product quality should result at a lower cost.

Virtual Manufacturing (VM) is an integrated, synthetic manufacturing environment developed to accurately simulate all levels of decision and control in a manufacturing enterprise. It allows you to understand your system, its' variability and the results thereof.

VM enables decision makers to virtually make proposed changes in products and processes, test the results, and quickly implement them, thus effectively responding to unanticipated change. Factory space can be "walked through" by virtual people insuring factory layouts account for human interface and ergonomic issues. Training of manufacturing personnel in decision making without impact to the efficient operation of the workplace can also be simulated.

VM can be used to visualize, understand and determine process plans, resulting in more consistent, accurate, and error-free process planning.

Benefits include: the enablement of agile manufacturing; increased understanding of product process flow, choke points, and a means of analyzing proposed changes and their resulting payoff prior to their physical implementation; and shortening product-life cycle, while enabling product initiation to begin further down the learning curve.

The processes of design and manufacture are by no means separate. Designs must be manufacturable and

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the manufacturer must create something which fulfills all the design criteria (for a review see Bayliss[1]). Thus we see a close tie between Design for Manufacturing (DFM) and Virtual Manufacturing. DFM is focused on ensuring that designed products are manufacturable.

The Virtual Manufacturing approach promises to provide better (more comprehensive and accurate) information to designers concerning product manufacturability. Designers can immediately know if a product can be produced, and if cost effective prototypes can be made. Design for manufacturing can become a reality by providing immediate design validation and feedback. Product designs can be modified to assure they conform to given manufacturing capabilities.

Boeing is in the early stages of benefiting from the potential benefits offered by employing Virtual Manufacturing. An overview representative of current technology applications and our vision for future technology advancements and their potential impact on our manufacturing environment are advanced.

CURRENT AND NEAR TERM USES OF VIRTUAL MANUFACTURING IN BOEING

Boeing began investigating the use of Virtual Manufacturing (VM) tools in the 1980's as a method to reduce product development time, cost and risk. Since that time, these tools have been used during the entire product development cycle, from concept development through production and product support. As the benefits of VM become known, it's use has been implemented earlier in the products life cycle where it has the most impact. Throughout the product life cycle, VM simulations can provide the best means of communicating:

- What is the product?
- How will it function?
- How will it be made?
- How will it be maintained?

This is especially important in today's defense procurement environment with very few big programs, and lots of small R&D and Demonstration /Validation (Dem/Val) efforts. The short duration and limited funding of these small programs necessitates answering the above questions concurrent with the design evolution, and communicating the answers in a manner that all the players understand. Use of a VM tool suite, made up of; CAD, assembly visualization, kinematic workcell simulation, NC verification, human factors simulation and discrete event factory simulations, provide the best method of doing this. Other tools, such as a photorendering capability, may be used to augment the tool suite for added communications benefit.

What is the Product?

During the Concept Development (CD) phase, the VM tools are used to quickly rough out what the product looks like and simulate the motion of moving parts to help determine if the concept design meets it's requirements. As the design matures in CAD, the VM simulations are updated to reflect the changes, and to allow the designs to be scrutinized for interference's that will affect form, fit and function. It is desirable to visualize and navigate through the assembly models. The ability to do this is limited within the CAD environment, but the components may be put together in a visualization tool such as Boeing's FlyThru® to quickly and easily provide large model viewing. Entire product assemblies, such as the Boeing Joint Strike Fighter (JSF) concept shown in Figure 1, may be viewed with FlyThru®, in this case the FlyThru® has been post processed in Engineering Animation's Viz-Lab®.

Prior to the development of visualization tools such as FlyThru®, designers had to rely upon physical mockups to provide information about interference's. The alternative was to take the time to load large CAD assembly models and create a series of section cuts to help find discrepant areas. Products like FlyThru allow designers to view assemblies internally to look for interference's or other assembly concerns visually as shown in Figure 2 of the Boeing JSF concept.

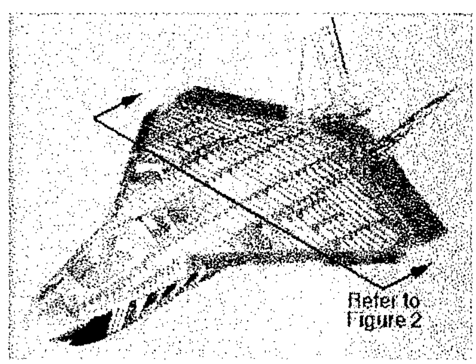

Figure 1
FlyThru® visualization of the Boeing JSF concept

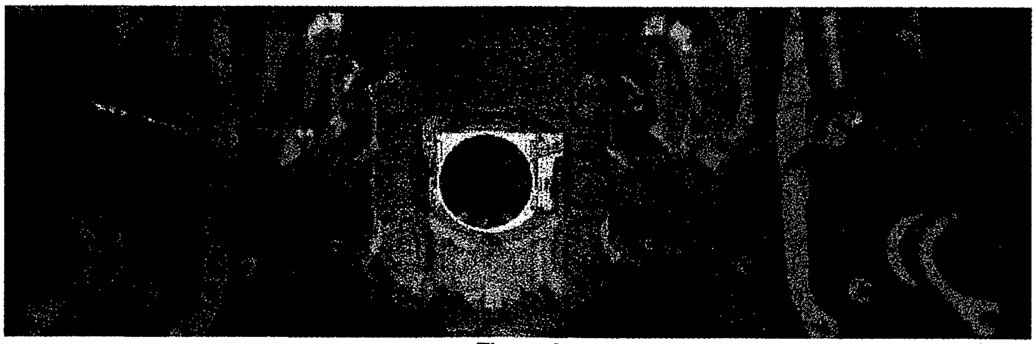

Figure 2
FlyThru internal view of the Boeing JSF concept

Automated interference checking of part model geometry's is available, along with the ability to visually generate assembly sequences. Because of the speed in which a FlyThru® model can be manipulated on screen, it is a great tool for Integrated Product Teams (IPT's) to use for sharing concepts and working through interface issues.

How will it Function?

In a virtual environment the product can be run through its paces, and the customer (as well as the whole IPT) can see how the product is supposed to function and provide timely input for design enhancements. The VM tool suite provides for reading in the CAD data and assigning motion, or kinematic data to the models to accurately represent how the final product will behave when moving. Kinematic simulation tools such as Deneb's IGRIP®, allow the user to simulate device motion by setting part translation/rotation parameters individually (forward kinematics) or automatically determine the individual part positions based on the desired final device positioning (inverse kinematics). In the case of the developmental robot weld shaver shown in Figure 3, the entire machine was simulated using inverse kinematics to insure that the device would perform it's intended function, and have the desired working envelope and reach capabilities. In this case, the robot was designed to shave down weld beads from electron beam welding of titanium. After the robot was built, the inverse kinematic model was used for the actual programming and tryout of the robot. In the past, the equipment would be built and any dimensional discrepancies would have to be reworked.

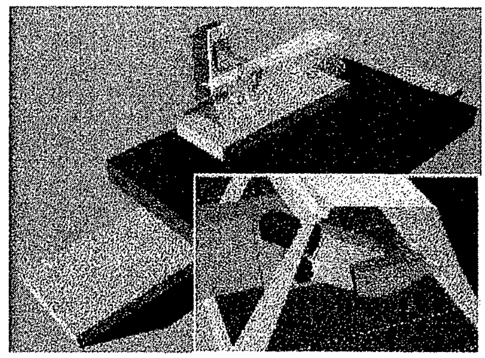

Figure 3
Kinematic model of a developmental robot

The same product and kinematic data needed for the VM simulations may be put into another package for photorealistic rendering. Photorealistic rendering (photorendering) is when geometric shapes are brought into a computer environment and the mathematical algorithms create an image, based on the defined parameters, that looks like a photograph. An example is shown in the Figure 4 picture of the International Space Station. This allows the product to be displayed in its end user environment with varying paint schemes, lighting and atmospheric conditions prior to fabrication

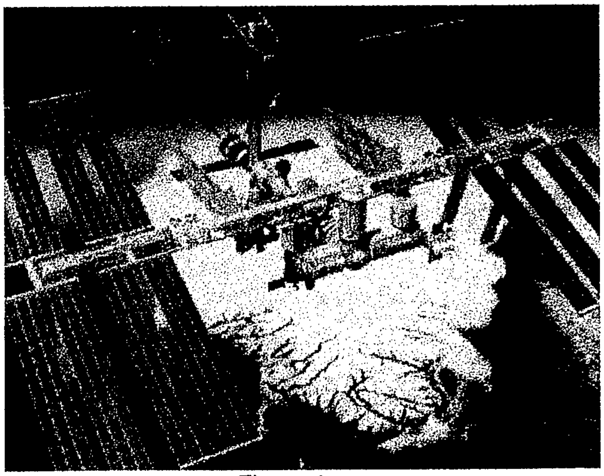

Figure 4
Photorealistic rendering of the Space Station

A photorendered image based on the actual part geometry as opposed to having an artist create an interpreted image, is very useful as a marketing tool. The tools are also sophisticated enough and utilize more engineering and science based algorithms to provide technical images to support tasks like camouflage development.

It is also possible to now simulate man-machine interfaces, or human factors in a VM simulation as well. This is important as we try to improve fabrication efficiency, where the layout of the workcell can affect not only how fast a worker can perform tasks, but also if the worker is apt to hurt him/her self in the process. The level of sophistication of the human models is constantly improving, providing better and better data on reach, posture, strain, repetitive motion disorders and other human factors criteria for the people involved with using, fabricating and maintaining our products.

Figure 5
Human factors simulation in the assembly of the JSF

In Figure 5, three workers are shown installing the lift nozzle into the Boeing JSF design. The primary interest for this VM simulation is to see if the nozzle can be lifted into place, and the bolts that attach it are all installable. This is a concern not only for the assembly of the airplane, but also the maintenance. This VM simulation was done using IGRIP® with the available Ergonomics option (IGRIP/Ergo). Prior to this technology, a physical mockup would have to be created for the area of interest, and possibly the entire aircraft. Mockups are expensive and time consuming to build, and do not always find all of the interference problems due to the constantly revising structural designs early on in a program.

How will it be Made?

VM simulations need to be at the heart of any 'Design for Manufacturing' and 'Design to Cost' effort. The ability to graphically simulate processes, tooling concepts, Media Try-Out's (MTO), assembly sequences, and factory flows is invaluable.

Process simulations show how a part is manipulated during processing, and includes all of the tooling and equipment required. This can be done for existing processes and equipment or to help validate new ones. Many things can be answered during process simulations. How many degrees of freedom does our new robot need to do the job? Does the equipment have adequate reach? Does the machine collide with the tooling? Does the tooling work as intended?

A good example of process simulation is the ISDS robotic paint facility in Seattle. Part geometry is read from CAD and placed into a VM process cell, in this case IGRIP, along with any associated tooling fixtures. Robot paths are generated on the part geometry using IGRIP®'s native algorithms or Boeing algorithms and, as shown in Figure 6 in the instance of the E-4B Milstar radome, IGRIP® checks to assure that the robot can reach all the path points without crashing the part or tooling. Parts such as the E-4B radome shown in Figure 6 would be nearly impossible to program using the traditional point to point programming methods. Additionally, the time required to manually program the part would tie up the robot and paint booth for about three times longer than by using simulation.

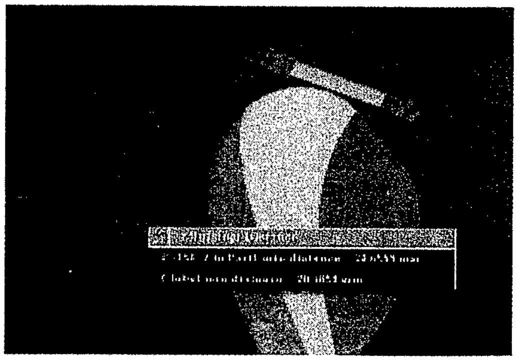

Figure 6
Reach/collision checking of the E-4B radome

After programming and checking for reach in this process case, a theoretical coat of paint can be applied in IGRIP® and checked for thickness and uniformity as shown in Figure 7 for the Darkstar wing. All the paths created using IGRIP®, along with the process data are downloaded to actually drive the robot. The paths and process data may also be uploaded from the robot for editing and archiving.

Figure 7
Simulated painting of the Darkstar wing

An NC machine tool MTO can be simulated using a similar method. Normally for an MTO the NC code is downloaded to the real host machine, and test run while cutting foam or wax at reduced speed. Any errors in the NC code that caused a gouge in the part, or crashes the machine tool into something is hopefully stopped prior to hardware damage. The NC code is then edited and re-MTO'd repeatedly until it is deemed acceptable. In a product like Deneb's V-NC®, an MTO can be done in a virtual environment. The part CAD geometry is read into a V-NC® workcell with a dimensionally and kinematically accurate model of the machine tool and all of the required machine fixtures and tools. A typical setup is shown in Figure 8, with a 3-axis mill cutting a metallic part.

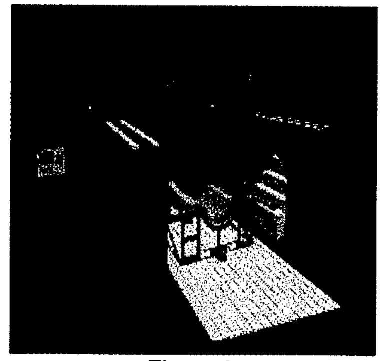

Figure 8
Virtual MTO of part machining

The NC code that would be used in the physical workcell is read in by V-NC®. A mimic file that has been previously written, emulates the characteristics of the real host machine and it's controller, reads the NC code and executes the code accordingly. Material removal can be simulated in this virtual environment as well as for more realistic simulations, and to check for unintentional gouging and missed areas.

Simulation is also used to show how individual components are assembled into sub-assemblies and ultimately the end product. Figure 9 shows a concept for the Boeing JSF main fuselage to wing join. An animated viewing of an assembly is really needed to adequately show how beneficial this is. In this instance, the fuselage is assembled with minimal tooling, and is laser aligned. Upon completion of the fuselage assembly, the main wing box is installed to the fuselage, and is also laser aligned prior to permanent attachment.

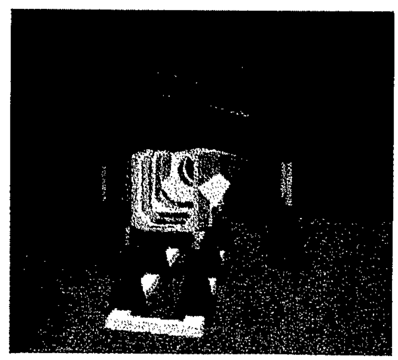

Figure 9
JSF wing to fuselage join

The assembly simulation can be used to validate the tooling concepts and assembly sequences, including the hydraulic, fuel and electrical systems installations. The simulation also provides feedback if a component cannot be installed, and if not, is it a problem in the design, tooling or assembly process sequence. Again, the alter-

native to VM simulation is to build physical mockups of any areas of concern. These are costly in both time and money, and are generally not kept up to date with minor engineering revisions. Mockups are usually laid out and assembled by hand, sometimes using wood or other materials instead of the actual part materials for ease of fabrication and to reduce their cost.

At the next level, the process cell and assembly simulations can be combined in a 3D factory level discrete event simulation to optimize factory layouts and analyze total product flow times, generate activity based cost estimates, and identify any bottlenecks through the entire production environment.

The simulations discussed in this section can provide a variety of outputs. Process and assembly sequences can be output as a data file to be used as a supplement to, or a replacement for a paper set of work instructions. Movie clips and images can be made to show the design/process intent for the shop, or the shop could also run the simulation if they had the hardware/software on the floor, to fully visualize the intent.

How will it be Maintained?

Many of the questions concerning the support and maintenance of a product are very similar to those arising during the manufacture of a product, the access, (removal) and installation of components. Simulation, especially with high fidelity human models, provides answers to these questions. Again, Figure 5 shows an IGRIP/Ergo® simulation of the JSF lift nozzle installation for either assembly or maintenance. Whether for assembly on the production line, or maintenance in the field, the human factors simulations can also provide analysis on posture and check for possible excessive strains and repetitive motion disorders. The simulations can be used as training aides by generating movie clips to supplement training documentation and be used as part of a computer based technical publication.

FUTURE DEVELOPMENTS IN VIRTUAL MANUFACTURING TECHNOLOGIES

Early evaluation of the human interfaces with product concepts for "customer-in-the-loop" and maintainability evaluations will become more user friendly, and cost effective, as virtual reality technologies mature. These evaluations will begin with immersing the customer in the initial product concepts and be used throughout the product development cycle. The ability to quickly determine the ability of humans to interface with the virtual prototype of the product design will also facilitate maintainability studies for life cycle costing analysis. Closer integration with the CAD data bases, Product Data Management (PDM) systems, Enterprise Resource Planning, SPC data and other corporate knowledge bases will enable the simulations to reflect more accurately the actual manufacturing environment anticipated. In the near term these inter-process communications will most likely be via Common Object Request Broker Architecture (CORBA) over the corporate Wide Area Network (WAN). Hopefully, the need for CAD translations into a separate format for simulations will be a thing of the past. Who knows, STEP may actually become a widely utilized product and process data format. High speed rendering hardware and software as well as sophisticated level of detail management will enable the users to visualize the full detail of the CAD model when necessary.

PDM systems will be expanded to include Process as well as Product configuration management as the implementation of Integrated Product and Process Development (IPT or concurrent engineering) really becomes part of the corporate culture. The physics based simulations of how the product functions as well as the manufacturing and maintenance processes will all be retained as part of the Smart Product Model. This will be true across the Virtual Enterprise as various sub-suppliers maintain a portion of the Smart Product Model for their product and process designs and make them available to their virtual enterprise team members over the Internet.

The product and process designs and simulations developed during the conceptual phases will be "fleshed out" during detail design and manufacturing planning. These simulations will then be available for "paperless shop floor instructions" and simulation based operator training on low cost platforms. For maintenance documentation and training, the CAD design and simulations will be converted to Web based tools for Web Enabled simulation based maintenance instructions that walk the maintenance personnel through the diagnostic and maintenance procedures.

The increasing band width will enable more collaborative engineering and should eliminate the requirement for flying to design review meetings. Since the product and process trade-off studies can now be visualized and discussed over the net between team members at different locations, these iterations will be more frequent and a greater level of optimization across the supply chain will be possible over a shorter period of time.

If the funding profiles for future programs are modified to support the utilization of these technologies from early in the concept development, and throughout the program, this will significantly enhance the life cycle affordability of future aircraft. This change in the acquisition funding will enable the defense contractors to modify their current processes to utilize these technologies, dramatically decreasing the time to field a new

aircraft, and optimize the product and process tradeoffs for manufacturing and maintenance. Initial implementations indicate that it is possible to achieve the goals of a 50% reduction in "time to market" with the associated product development savings and a 25 to 30 percent reduction in life cycle costs. This truly addresses the affordability problem facing the military aircraft manufacturers.

[1] Bayliss, G.; Taylor, R.; Bowyer, A.; Willis, P., "A Virtual Workshop for Design by Manufacture."

Virtual Manufacturing for Composites

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October 1997

Summary

The geometry based aircraft design to manufacturing process is described, highlighting the extensive use of simulation activities along its phases to verify the geometry. It is shown that the manufacturing simulation has an exceptional role in minimizing or even avoiding global iteration loops.
In addition, some wording is defined in the world of virtual manufacturing to be able to position the different software developments.
Based on this information two examples are shown - the composite stiffener technology and the composite skin technology - both based on prepreg tape targeting for high performance aircraft structures.
Due to the full usage of all neccessary material-, manufacturing- and machine data right from the first beginning of the design it is demonstrated that a fully automatic NC-code generation can be achieved already at the end of the engineer´s design process producing verified manufacturable data without any additional human interaction based on the designed geometry. By means of this, time consuming iteration loops coming back from the manufacturing phases and creating local iteration loops to the structural analysis are avoided.
Real examples of this „virtual manufacturing"-process are indicating 10 to 50 times faster processes compared to existing methods.
Finally, for both manufacturing technologies the integration with the corresponding optimization code is explained, outlining the important issues in this field.

1. Preface

Virtual Manufacturing is basically the simulation of a specific manufacturing process with the help of computer software. By means of this, expensive actual manufacturing tests including back iteration loops to earlier process steps can be reduced or even avoided. This has been recognized since a couple of years; the results are increasing software developments in this field.
However, most of these developments are based on existing NC-software. In nearly all cases virtual manufacturing is handled as an element downstream of the design to manufacturing process as an additional step after the design has been finished.
The reason for this is that the NC-software suppliers have a much closer knowledge about the capabilities and constraints of the NC-machines than the CAD-software suppliers. This knowledge is a precondition for manufacturing simulation.
As some companies have had success in a different approach (Ref. 1), which applied manufacturing simulation already within the design process, this paper wants to evaluate at the beginning a deeper understanding of the aircraft design to manufacturing process. Based on this a definition of virtual manufacturing is given, which leads directly to a discussion where to position virtual manufacturing within the design process.

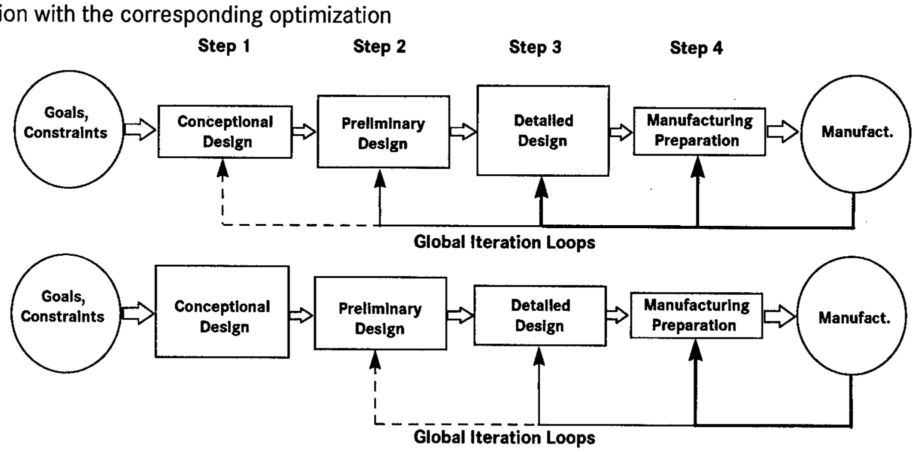

Fig. 1 Aircraft Design to Manufacturing Process (Geometry based activities only)

Paper presented at the AGARD SMP Meeting on "Virtual Manufacturing", held in Aalborg, Denmark, 13-14 October 1997, and published in R-821.

2. The Aircraft Design to Manufacturing Process

A view of the aircraft design to manufacturing process is shown in Fig. 1 (upper process). Hereby, the geometry based activities are displayed in 4 steps. The initiation of the process are goals and constraints for the aircraft. Goals are values to be minimized e.g. costs or maximized e.g. fuel effeciency or other performance values. Constraints are values to be kept above or below a certain limit; examples are roll rate, take-off distance and similar values.

The formulation of the goals with their constraints leads to the conceptual design phase (step 1). Characteristic for this phase is that most analysis models are parameter based and that the already existing multidisciplinary design process is controlled by a manual optimization mode to keep the control of the results in relation to the input variables completely in the aircraft designers hand. Manufacturability is not taken into account, because detailed geometry is not known at this stage. The target of this process step is to find an aircraft design to maximize the goals by simultaneously keeping the constraints. The results must be accurate enough to prove the concept for obtaining financial contract to continue the project.

Step 2 is the preliminary design phase. Characteristics are relatively rough geometry models, the so called key diagrams, global analyses for the structure and global structural optimization as an element to minimize the iteration loop between geometry generation and geometry verification.
Aspects for manufacturing simulations are not possible because the geometry of the structure is not detailed enough.

The following step (step 3), the detailed design phase, leads to accurate, three dimensional geometry, so detailed simulations can take place. Typical within this phase are detailed final geometry models, detailed analysis in every respect and the use of local optimization activities. The results are verified aircraft structure data ready to transfer to the plant level.
On this level, step 4, tool design is done, NC-code is generated and manufacturability is tested either by virtual simulation or by actual simulation. Anything which occurs there, leads to an iteration loop back to earlier process phases. This can be iterations up to the preliminary design phase. Changes within the conceptual design phase should be avoided in any case.

It has been recognized in recent years, that if one puts more activity in the initial phases, iteration loops can be avoided or minimized (see Fig. 1, lower process). But what must be available to be able to do things earlier? Here we have to take a closer look at the side activities of the geometry process. In Fig. 2 the side activities of the geometry process are classified in simulation activities and testing activities.

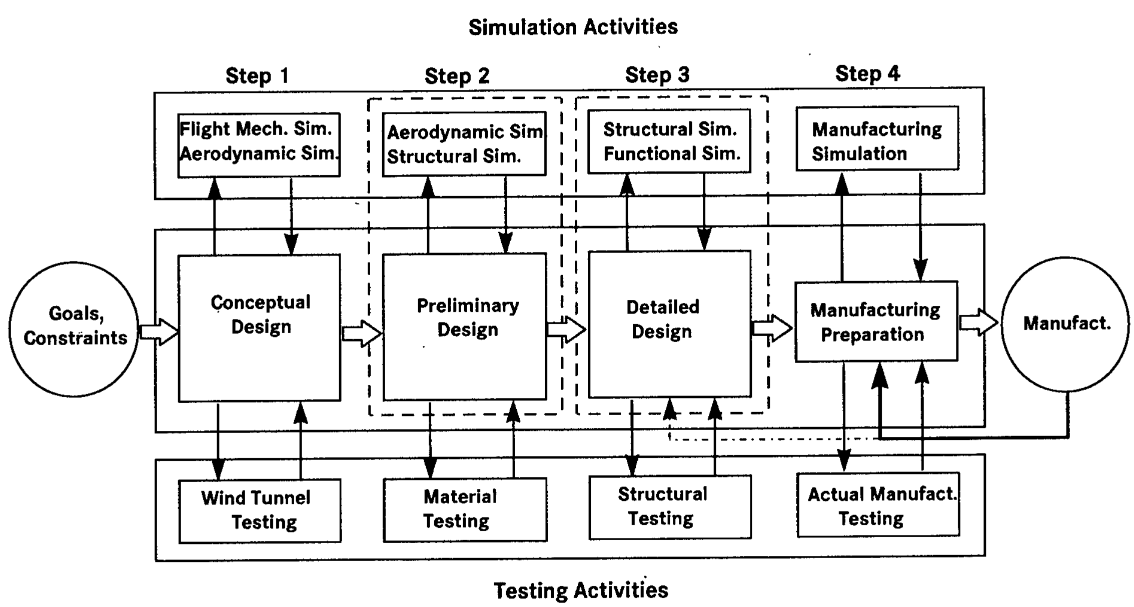

Fig. 2 Aircraft Design to Manufacturing Process with Verification Activities

The simulation activities are all activities to simulate anything which happens or could happen in the life of the aircraft; starting from manufacturing to aircraft support or even to the aircraft disposal process. These are flight mechanic and flight performance simulations to calculate the motion of the aircraft with its performance, aerodynamic simulations to calculate the loads on the structure, and also structural simulation to calculate the behaviour of the structure at loads which could occure in lifetime.
The testing activities are all activities which use real structure or real models to „simulate" anything which still cannot be simulated by software. Testing activities are expensive and time consuming, so if more confidence for software simulation, which has constantly increasing capabilities, is achieved, the lower side activities in the process of Fig. 2 decreases, whereas the upper side activities increases. A typical example is functional simulation during the detailed design phase, which leads to a digital mock-up, avoiding physical mock-ups.
The use of optimization codes is marked by dotted lines in step 2 and step 3 in Fig. 2. In this manner a new definition for optimization is the minimization of the local iteration loops between geometry design and the related simulations. With increasing numbers of disciplines to be taken into account (multidisciplinary design optimization) the number of iterations is decreasing.
An exceptual role within all these simulation activities is given by the manufacturing simulation or virtual manufacturing. The use of these new capabilities not only minimizes local iteration loops, it also minimizes or even avoids global iteration loops.

3. When to apply „Virtual Manufacturing"

As a rule resulting from the previous chapter, virtual manufacturing should be used as early as possible. However, due to the need of detailed geometry, this could be earliest in the detailed design phase.

On the other hand, the iteration loop between the detailed and preliminary design phase has a remarkable impact on process time. The existance of detailed part geometry already within the preliminary design phase should be a goal. Here the developments in new CAD-systems help to reach this goal. As an example feature or ruled based design dramatically reduces the geometry generation time to a fraction where it was years before. The use of very fast geometry generation tools is the key solution to bring virtual manufacturing one phase further upstream the process and even to melt the step 2 and step 3 into one step (Fig. 3, new step 2).

The need to start preliminary design with key diagrams arose from need to be able to quickly generate a geometry for first verifications. If modern CAD-tools provide very fast methods to generate the structure in actual detailed 3D-geometry, then there is no need anymore for this intermediate step. Within the same time, actual geometry can be created and verified against different constraints by simulations including manufacturing simulation which has the most influence to process time reductions.
The remaining work of step 4 in Fig. 2 will be in future an automated „side product" of step 2 in Fig. 3.
The melting of the preliminary phase into the detailed design phase does not mean that there is no preliminary design activity anymore; within this step the first iterations are the preliminary design phase (n = 1-2), whereas the final iterations are the detailed design phase. Common for both phases within this one step is that from the beginning the same software tools will be used including all the relevant simulation tools; only the accuracy of the model will be different along the time axis.
The last activity will be a semiautomatic generation of NC-codes coming from the simulation software tools. As already mentioned earlier, very fast geometry generation tools and verified simulation tools are preassumptions for this short process; also discrete geometry capability is necessary for the optimization tools.

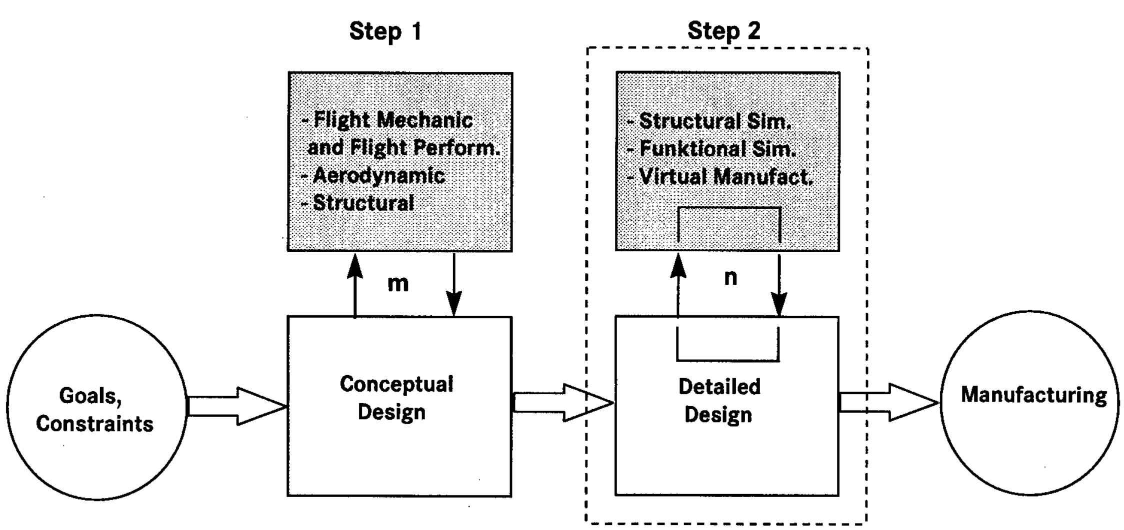

Fig. 3 Aircraft Design to Manufacturing Process (Strongly Simulation Tool supported)

4. Definition of Virtual Manufacturing

Before continuing with the description of some typical applications for virtual manufacturing clear definitions should be made; this will help to position the different approaches from the present available software developments in this field.

„Manufacturing simulation“ is the simulation of a discrete manufacturing technology with the help of a computer software. With this definition it is not visible if the complete manufacturing technology is simulated or only an important part of it.
A „simulation“ can be achieved by simply programming „rules“ into the system or by developing an analysis tool either based on „discretisized geometry“ or on „analytical geometry“.
An example for manufacturing simulation by rules is single axis sheet metal bending; the rules could be certain values of bending radii for certain sheet metal thicknesses and type of materials.
An example for manufacturing simulation by discretisized geometry is multi-axis sheet metal bending simulated by a finite element approach.
If all aspects of the manufacturing technology are simulated, then we are talking about „virtual manufacturing simulation“ or „virtual manufacturing“. A typical example is the simulation of a milling process taking into account everything from cutting tool behaviours to the simulation of the motion of the milling maching itself to avoid collision.

Another important definition is the expression „accurate virtual manufacturing“. This is used for a 100% simulation; that means everything is taken into account to avoid non-manufacturabilities. The „accurate virtual manufacturing“ is a precondition for a fully automated NC-code generation.
If the simulation program is capable of being used during the design phase, it is called „design integrated virtual manufacturing“.

5. Virtual Manufacturing for Composites

Software developments for virtual manufacturing simulation have its origin mostly in existing programs, like NC-code based tool simulation for milling machines; so this type of manufacturing technology had never the chance to start from a „green table“ again. This was the case with the technology of automated tapelaying machines and composite stiffener manufacturing machines, as before they had been introduced, there was only manual composite manufacturing technology existent, and there was no necessity for NC-code generation programs.
In addition, within the above composite technologies there is one process missing, that is the design of additional part geometry for the purpose of manufacturing. This and the fact that most composite tooling do not need an individual design, made it possible to achieve a very fast process.
As an example the composite skin manufacturing technology and the composite stiffener technology are discussed in detail within the next chapters.

6. Example Composite Skin Manufacturing Technology

One of the first successful examples for real virtual manufacturing is the simulation of the tapelaying process for the design of aircraft skin structures [Ref. 3, 4]. This development was based on the need that the tape courses and tape cuts by a fourteen axis tapelaying machine (Fig. 4) for complex 3D-geometry cannot be programmed anymore on the plant level. In Fig. 5 you can see the skin of a fighter fuselage made out of 8500 single tapes. The only way is to automatically derive the NC-code from the geometry data during the design phase. As the manufacturing process is based on laying one tape on another, the belonging simulation process has to do the same. Otherwise no direct action can be introduced by the designers if non manufacturability occurs. An example of the simulation of a ply build up is shown in Fig. 6. The ply periphery initially is created by the designer or comes already from an optimization programm [Ref. 2]. Then each tape is simulated taking into account all machine contraints from steering radii to cutting feature based on the uncured prepreg material data. A non manufacturability stops the process and a solution by the designer has to be found. This can either be changing the start position of the first tape within the ply or changing the periphery to avoid cutting problems. In the worst case a cut along a tape has to be ordered from the software to avoid large gaps between tapes. After each ply the software has to create the exact offset surface for accurate simulation of the following plies.

This tape by tape and ply by ply simulation is an online functionality and is certainly time consuming depending on the necessary actions needed to achieve manufacturability. Production examples show simulation times about three hours on a high end work station for a 65 ply wing skin with nearly no non-manufacturability occuring during the simulation process. Preparation labor to define interactively the peripheries and the definition of the logical ply buildup-matrix were about one manweek, depending of course on a proper functionality of the software and a trained engineer. The result was directly usable machine data, ready for the lay down process. Compared to standard programming software based iterations, the improvement in process time are at least factor ten.
Presently, an extension of the simulation process for collision checking of the tapelaying machine is planned. In Fig. 7 you see an equivalent example of a fiber placement machine collision simulation.

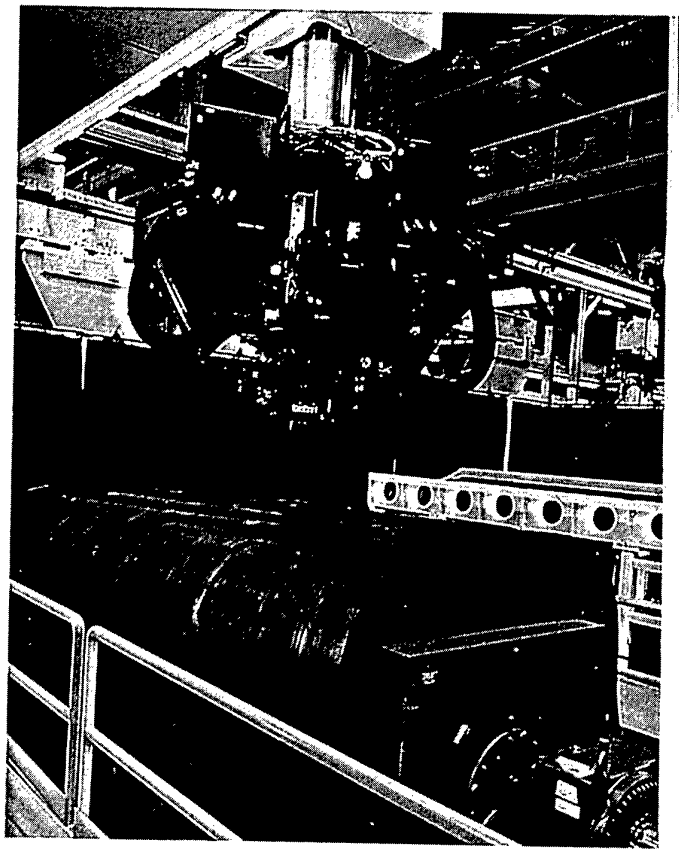

Fig. 4 14-axis tapelaying machine above a positive fuselage tool

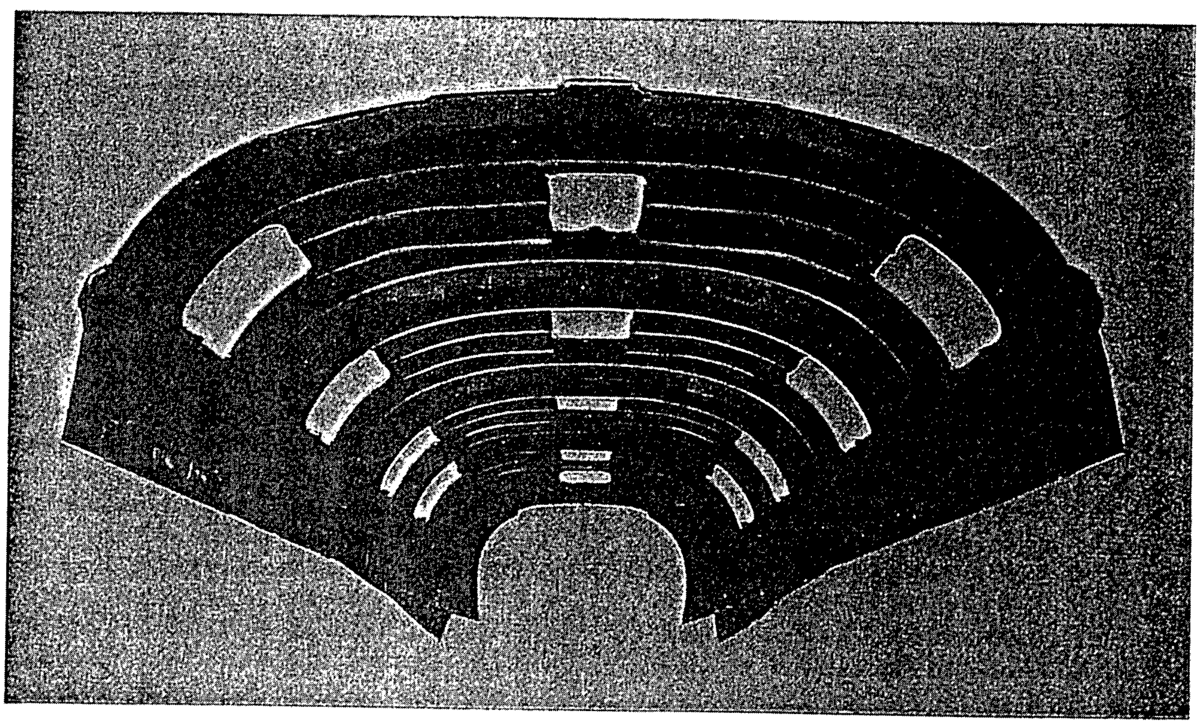

Fig. 5 Fighter composite fuselage skin with stiffeners

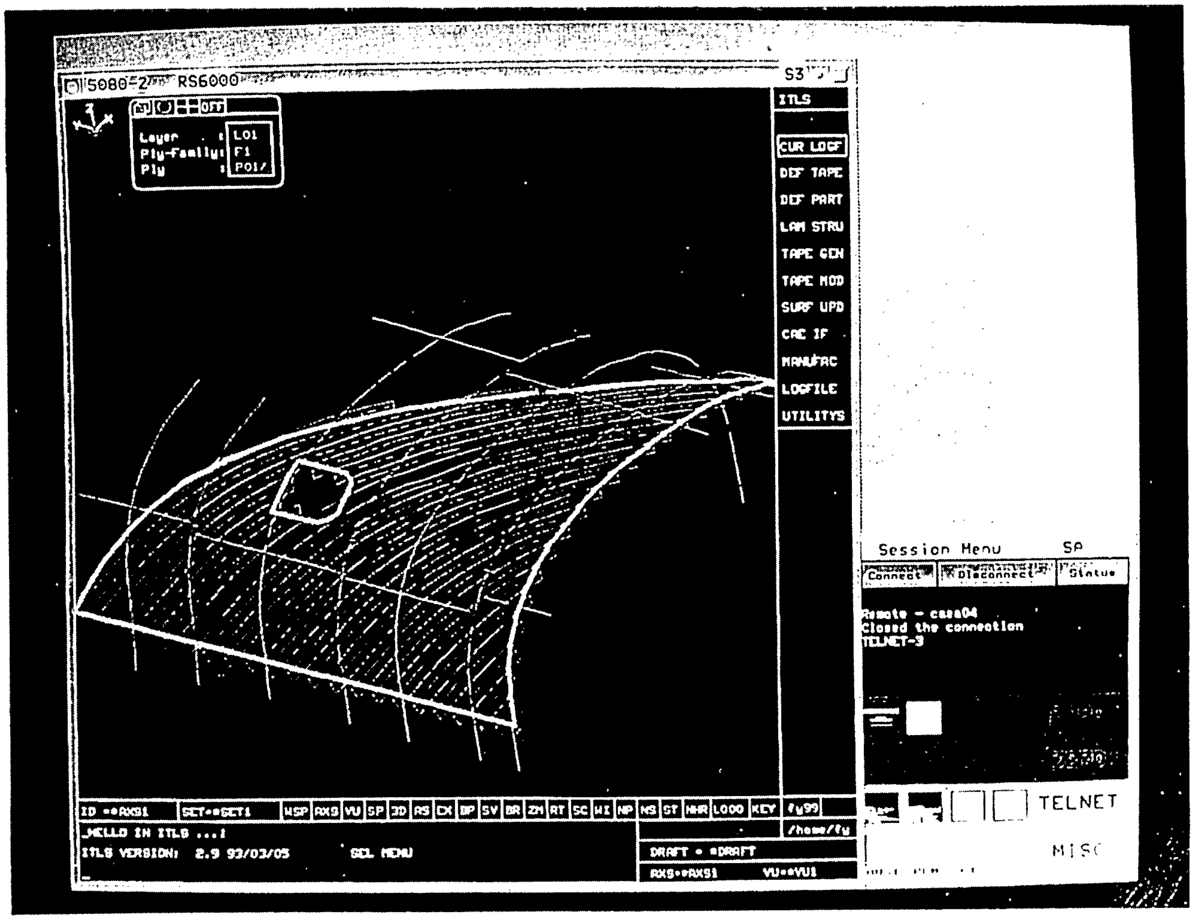

Fig. 6 Virtual tapelaying of a fuselage laminate within a CAD-session

Fig. 7 Virtual machine simulation for anti collision checking

7. Example Composite Stiffener Technology

Based on the success of the tapelaying simulation and the need for completing a monolithic highly loaded aircraft structure by automated manufacturing a composite stiffener virtual manufacturing process was developed. For complex shaped skins we use a so called C-Z-stiffener, which is assembled from three ply build-ups, the C-, the Z- and the foot laminate (see Fig.8). The first two ply build-ups already have an unidirectional top laminate for high stringer stiffness. The hot transformed stiffener will be placed combined with a partly soft tooling directly into the uncured skin for simultaneous cocuring in the autoclave.

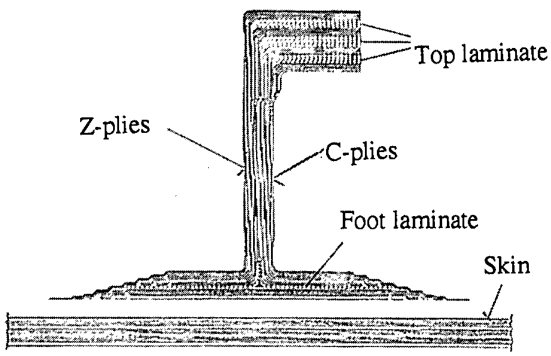

Fig. 8 C-Z-stiffener cross section

The related automized manufacturing technology can be seen in Fig. 9. At the beginning a fast two axis tapelayer with straight cutting capability is used to lay down one ply on a moving transport foil. Then a ultrasonic cutter cuts along the actual ply periphery with minimum scrap compared to prepreg fabric with Gerber cutter. In the next step a robot places the individual plies in the right orientation onto the transforming tool; the final step is the hot forming process around the assembled tooling.

Necessary data from a virtual manufacturing process are the ply peripheries for cutting, the orientation for placing each ply and the tool geometry for the transforming process and the positioning.

As the simulation is a transforming of the complete assembled laminate, the software has to do exactly the same.

So the initial step for this manufacturing technology is to create the stiffener geometry. To avoid complex mathematical related workload for the designer to create 3D-geometry with standard CAD-functionalities a ruled based feature orientated approach is used. A feature here is a specific stiffener topology. In our case, by selecting the C-Z-topology and by defining the offset surface, where the top laminate of the stiffener has to be placed and the stiffener end geometry including the composite input of number of plies for the shear section and the top laminate, the complete geometry can be created by a push of a button. Integrated into this functionality is a set of rules to secure e.g. ply drop off and partitioning of the plies to achieve fiber orientation within certain limits (Fig. 10).

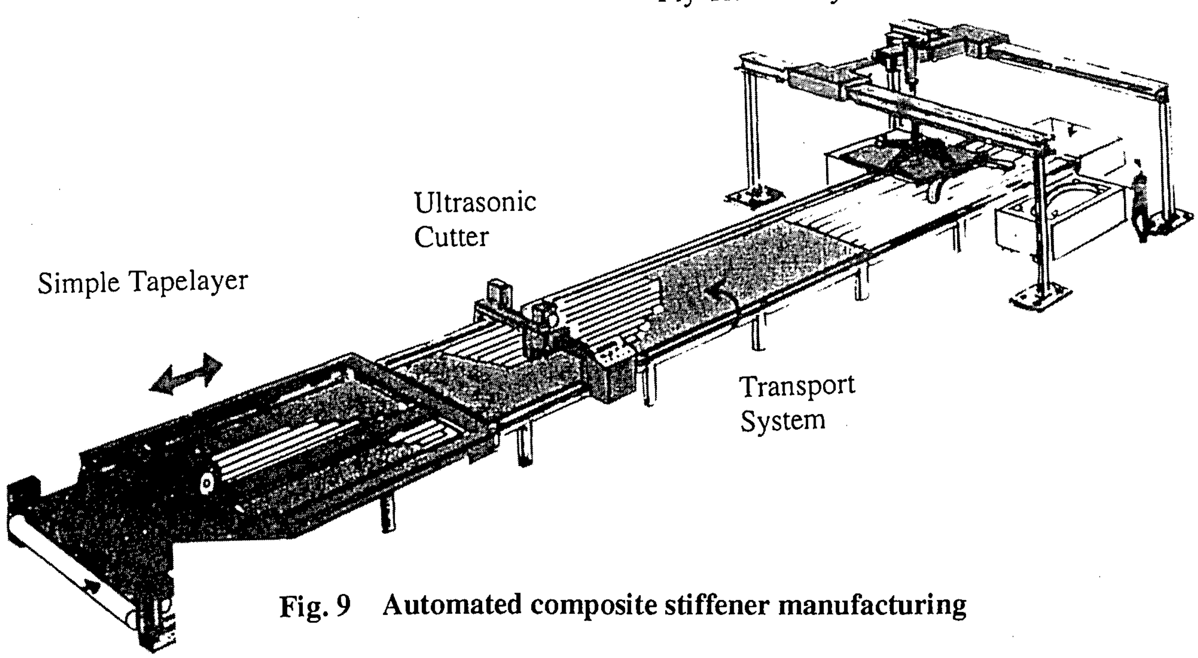

Fig. 9 Automated composite stiffener manufacturing

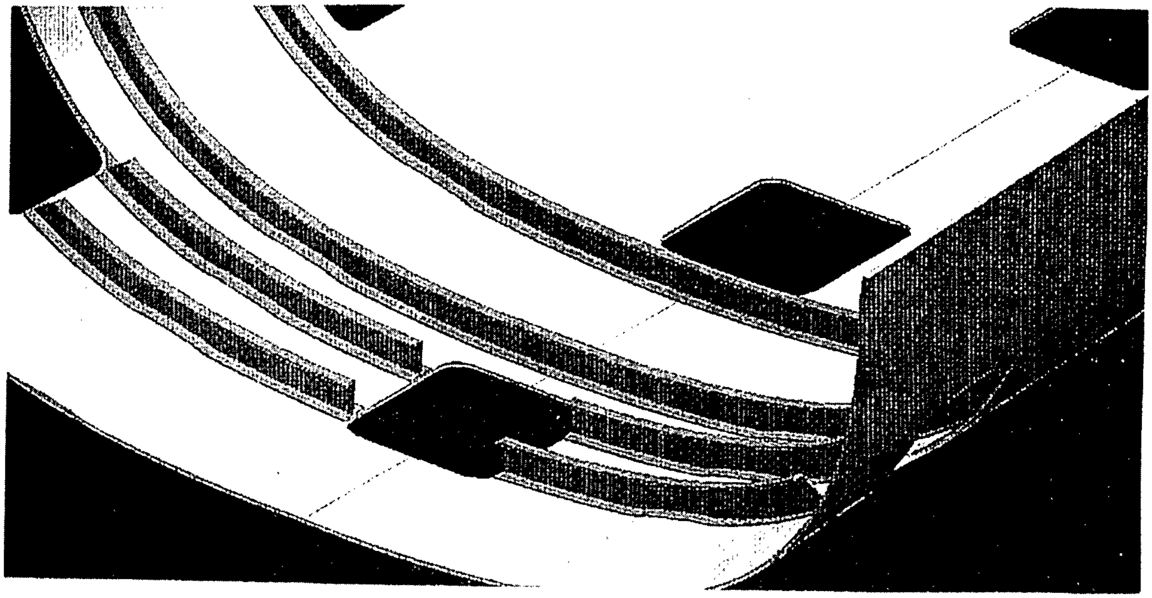

Fig. 10 Feature based stiffener geometry generation

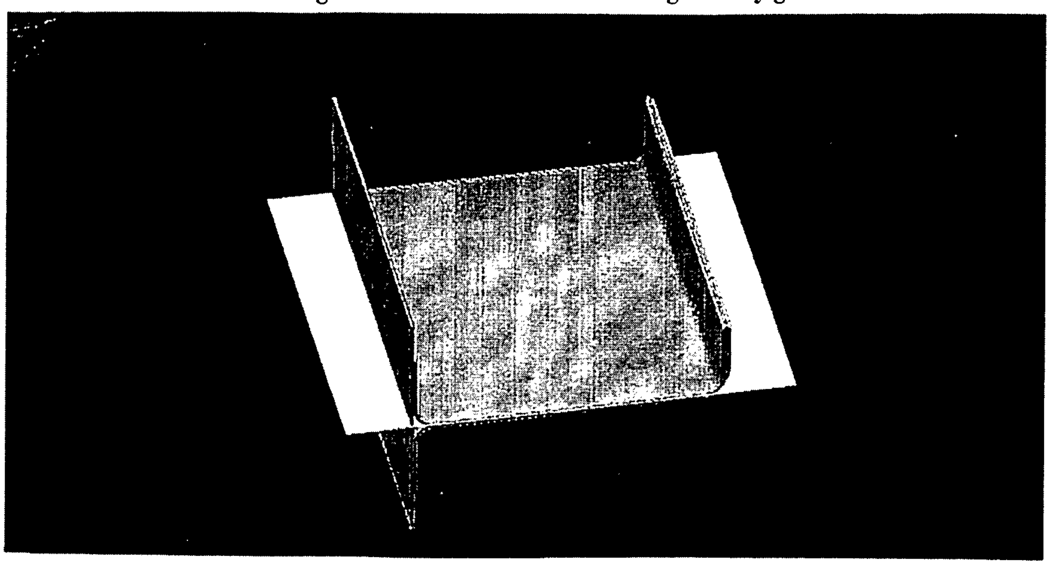

Fig. 11 Simulation of the laminate transforming process

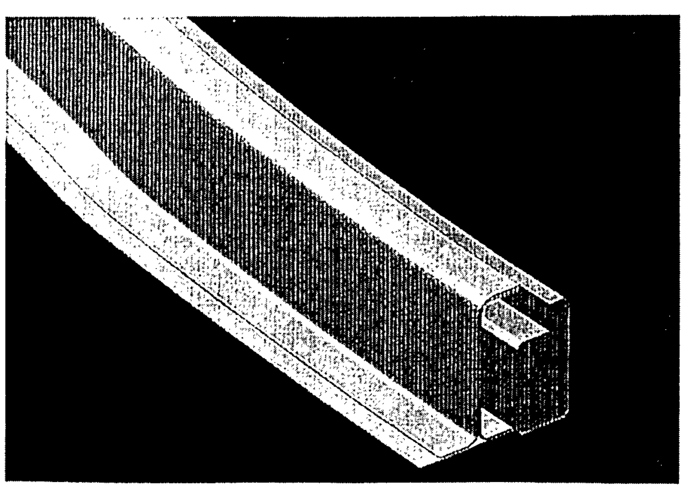

Fig. 12 Feature based tool geometry generation

The next step is the simulation of the transforming process; this means the software calculates those peripheries of each individual ply within the complete laminate, which gives after transforming it from flat the final stiffener geometry. The behaviour of the movement of the fibers within the uncured resin has to be taken into account. To obtain still an acceptable response time for this interactive design process, a compromise between theory and usability had to be found and verified by tests. The result of this step are the individual ply peripheries for the cutter and the lay down orientation for the placement robot (Fig. 11).
In case of a non-manufacturability the stiffener software automatically splits up the plies to avoid disorientation of the local fibers and deviation from calculated global fiber orientation.
The third and last step is the also ruled based automatic generation of the tool geometry for forming the silicon moulds including their stiffening (Fig. 12).

Practical test for a production stiffener shows a stiffener creation time of about half an hour including the generation of complete manufacturing data for the machine. This means, compared to the traditional 2-D paper based process, an acceleration of process time by factor 50. It has to be mentioned, that this only can be achieved by very specifically developed software.

8. Introduction of Optimization Code using Virtual Manufacturing Constraints

An additional process improvement can be achieved by using mathematical optimization code, which already takes into account the major virtual manufacturing constraints.
This solution aims at a reduction of the remaining iteration loops between the design process and the analysis process (see Fig. 3, iteration loop n). A first realization was made in combination with the optimization code LAGRANGE [Ref. 2] and the tapelaying simulation software ITLS [Ref. 3]. Test examples show here also a remarkable speed up of the process due to the reduction of the CAD-CAE iteration loops. Essential in this field is that a compromise between the relevant constraints and the minimization of the number of physically different constraints has to be found, otherwise the optimization comes to an academic solution or does not converge. In the case of automated tapelaying the ply drop-off rule and the tape steering limitation were selected. The cutting constraints were neglected to avoid convergence problems.

Remarkable is the complete paperless data flow from the optimization code directly into the simulation code based on the real CAD-geometry for defining the manufacturing constraints [Ref. 5, 6].

9. Results for Future Virtual Manufacturing Process Design

Learning from practical test results the following rules should be taken into account to avoid problems:

Software devolpment and software maintenance is very expensive; in addition, if a software is once introduced and used for production it is very expensive to get rid of it. Therfore it is very critical to establish the right strategy for the development or the ordering of such manufacturing simulation tools. In the worst case a company has as many different software tools as they have machine suppliers multiplied by the number of used CAD-systems. The key to avoid this, is to force the software supplier and the machine supplier to a standard not only for the data to the machine, but also for the data describing the machine constraints, which enables a more neutral simulation software package.
Very important is where the „cut" is made between the machine simulation software and the machine control software. It is a must that the machine control software is supplied by the machine manufacturer; it should be based on the pure geometry of the part coming from the design office. Otherwise the simulation software has to be changed anytime when the machine builder makes some changes on his machine or machine controls.
The geometry data have to be generated during the simulation phase by taking into account all machine constraints including global and local machine geometry for collision checking.
Another important decision is whether to integrate the simulation software into the CAD-system or not. An advantage of an integrated simulation software is that the designers, who have to use this functionality, have only one software, implicating minimum training and maintance; another advantage is that during the iteration loops within the simulation process, when non manufacturabilities occur, changes to the geometry have to be made. The functionality of the CAD-system can be used to do this, avoiding duplicating these functionalities within the simulation software. Another advantage is that there is no additional activity necessary for integrating a separate tool into the data management tools.

Disadvantages are the very high dependancy from the CAD-tool and its supplier and the exploding functionality of the CAD-tool, when all the simulated there. A complex coordination by each company has to be carried out between the different machine suppliers and the CAD-supplier to secure a high conformaty and integrity; this is sometimes not achievable as competition politics may be preventing this. This disadvantage especially has a high weight as long as there is no reliable standardization in the domain of machine constraint parametrization.
Due to the fact that user surface standards (e.g. OSF-Motif) and graphic standards (e.g. OpenGL) is more reliable and more computer hardware independant nowadays, it is recommended to head for CAD-system independant simulation software. Within the process the designers have to switch from the CAD-system, where they initially defined the geometry, to the simulation system. Because most manufacturing technologies imply specialized designers it is possible that they can remain most of their working time within the simulation system; necessary changes to adopt the geometry can be achieved by limited geometry functionality within the simulation tool. Again standardized geometry libraries help to mimimize the development efforts.
The data flow to the machine directly can happen from the simulation software, whereas the finalized geometry can be delivered back to the main CAD-system.

In general, each individual manufacturing technology needs a specific simulation software if the related topological architecture of the software is different. To evaluate this in relation with the necessary simulation theory a study was made how to classify the composite manufacturing technologies specifically for this. The result of this is seen in Fig. 13 for composite skin manufacturing technologies and in Fig. 14 for composite stiffener manufacturing technologies. In dotted boxes are indicated the presently available software modules on the market.

In principle all manufacturing technologies can already be simulated within the design process. However, for the most used technologies, e.g. the multiaxis NC-milling machine, the variety of different machines and the already available downstream simulation software is preventing this real virtual manufacturing approach. Standardization efforts for the complete machine information file could accelerate this new software development activities.

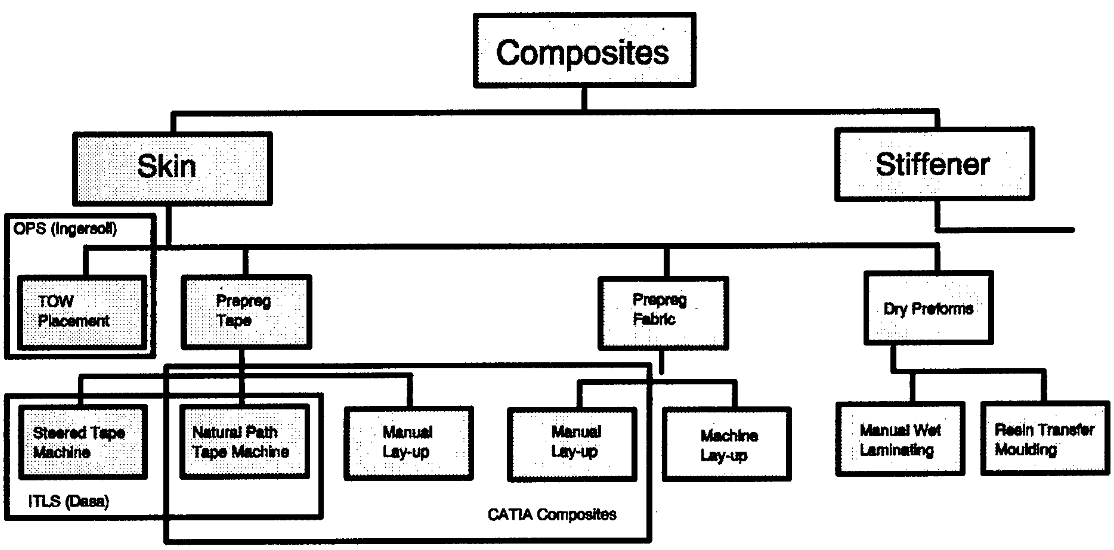

Fig. 13 Classification schema for composite skin manufacturing technologies

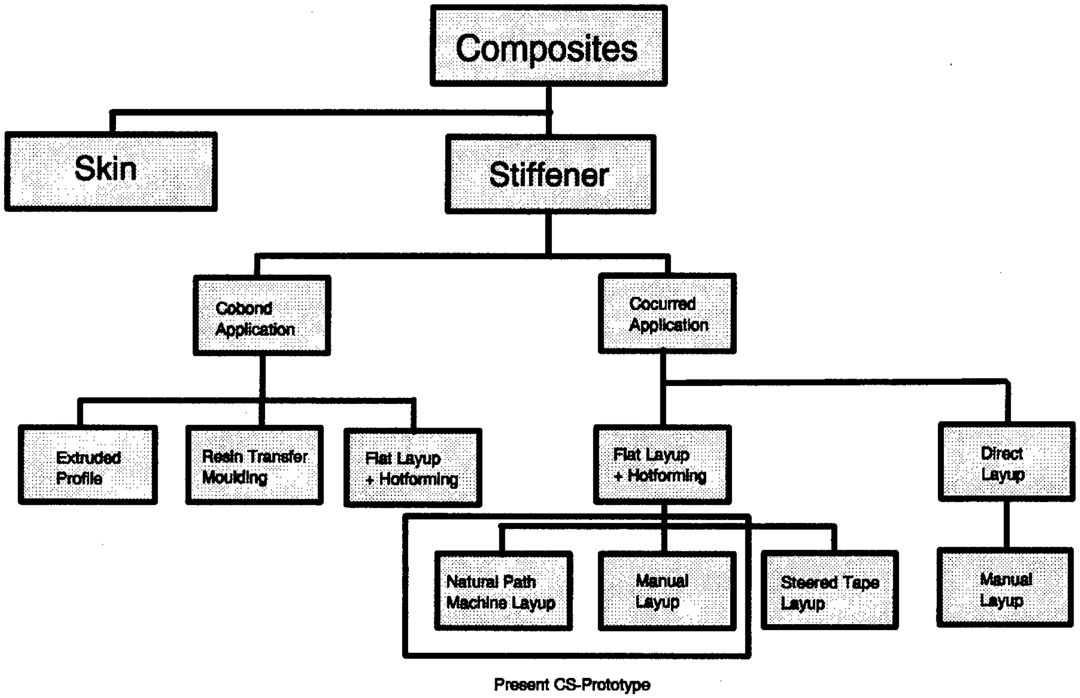

Fig. 14 Classification schema for composite stiffener manufacturing technologies

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An Object-Oriented Taxonomy for Part and Process Design

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Summary

This paper describes an object-oriented data/knowledge model for interactive part and process design. This model is employed in a Computer Aided Process Planning (CAPP) kernel. Objects are used to represent the process planning information. Each data-object has attributes, a set of methods, a constructor, etc. The information contained in such object can be supplied either by a software expert module or by the human expert, through an interface that is provided for each type of object. Consulted expert modules will take into account the information that was added by the human expert (or by earlier consulted expert modules). Moreover, the interface to human expert allows him/her to verify, accept or alter the information generated by an expert module, at any time.

Objects with partial information (empty attributes, attributes that describe intervals or constraints or multiple discrete values,...) will be called virtual objects, while objects that are unambiguously determined by the information contained in their attributes will be called physical objects. The paper elaborates on the distinct knowledge sources and their relation with the data model. It explains, for each knowledge source, its representation and its instantiation. Further, the aspect virtual versus physical object is handled; i.e. how virtual objects evolve towards physical objects by providing them with necessary information.

Keywords : Computer Aided Process Planning, knowledge based CAPP, feature based CAPP.

Introduction

The magnitude of the CAPP problem has been consistently underestimated. The very nature of human problem solving has probably been the primary reason for this dilemma. Recent research has shown that human cognition, when addressed to a problem like process planning, incorporates a vast network of concepts and perceptions. Indeed, human beings tend to perform planning in an opportunistic fashion by intermittently postulating goals, generating sub-goals, gathering constraints, reformulating ideas, exploring consequences, etc., until an acceptable solution has been reached. Therefore, process engineers do not adhere to rigid CAPP algorithms for the specification of which step to take, given every possible situation.[1]

To force complete order on the process planning procedure through the development of a rigid process planning algorithm, is to lose most of what makes human process engineers such adaptable problem solvers. It is clear that an effective CAPP system should provide comprehensive means for user interaction. Ultimately, to computerise/automate the process planning problem is to understand what is at the core of human cognition and to transform this into models.

In this paper, a model is presented for an interactive CAPP kernel. This kernel is based on a blackboard system architecture, because this approach represents a good approximation of the way process planners plan in real world.[2] Indeed, they do not always plan in a hierarchically layered manner, but rather, they will often employ an opportunistic reasoning, beginning with difficult features that constrain the plan, making preliminary decisions based on those features, and exploring the

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ramifications of those decisions, independent of other part features.

In a first section of this paper, the object-oriented taxonomy of the developed CAPP kernel is addressed. A second section specifies the diverse knowledge sources and their relation with the data models is explained.

Blackboard based CAPP

Process planning deals with many diverse, specialised applications (call it process planning tasks) that have to be integrated in some way. Some planning tasks can be executed arbitrarily (e.g. selection of a specific tool before determining the machine or vice versa). However, the outcome of each task can (will) depend on the results returned by previously completed planning tasks (e.g. the selected tool can only be mounted on a limited set of machining centres). Furthermore, the knowledge representation in each planning application can be different (e.g. rule-base, Petri-net, neural net, fuzzy logic, table, algorithm,...). Such complex environment can typically be handled by a blackboard system.[3,4]

The architecture of a blackboard system can be seen as a number of people sitting in front of a blackboard. These people are independent specialists, working together to solve a problem, using the blackboard as the workspace for developing the solution. Problem solving begins when the problem statement and initial data are written onto the blackboard. The specialists watch the blackboard, looking for an opportunity to apply their expertise to the developing solution. When a specialist finds sufficient information to make a contribution, he records his contribution on the blackboard, solving a part of the problem and making new information available for other experts. This process of adding contributions onto the blackboard continues until the problem has been solved. A manager, separate from the individual experts, attempts to keep problem solving on track and ensures that all crucial aspects of the problem are receiving attention.

Translating this metaphor into a computerised blackboard system, the distinct specialists should be considered as expert modules and the blackboard as a global database containing input data, partial solutions and other data in various problem solving states.

For triggering and controlling these expert modules, three ways of managing the blackboard could be distinguished :[2]

- User driven : The decision of which expert module (or simply expert) to call is in the hands of the user.
- Automatic triggering : The experts constantly observe the information on the blackboard and add new information as soon as they can. The manager mediates if experts have conflicting goals.
- Scenario driven : A scenario is designed on beforehand, that determines the behaviour and sequence of calling expert modules. This is the procedure used in the PART system, described in [van Houten 91] and [Jonkers 92] or the DTM/CAPP system presented in [Jasperse 95].[5-7]

In the present development, a user driven approach for managing the blackboard is chosen. It not only promotes the interactiveness or human involvement; it also makes the CAPP system transparent and facilitates the understanding of its structure, behaviour and outcome. The difference with (and advantage over) the PART or DTM/CAPP system is that the different expert modules can be called in an arbitrary order, instead of according a specific sequence. The user can for instance decide to do first the machine selection, and then the set-up planning, or vice versa. Each software expert will use the already available information on the blackboard and will prompt the user for missing information. Another advantage is that these expert modules can be called more than once. Moreover, the 'automatic triggering' and 'scenario driven' approaches could easily be implemented in a later stage, since full flexibility is being offered. In this case, only the blackboard manager need some extra capabilities.

The next paragraph explains how the blackboard data are organised. It proposes an object-oriented model that allows expert modules as well as the human expert to produce the information.

An object-oriented Blackboard model

Objects are used to represent the blackboard information. Each data-object has attributes (slots that contain information), a set of methods, a constructor, etc. for handling this object (figure 1).

The information contained in such object can be supplied by :

- an *expert module* that consults the appropriate knowledge source,
- the *human expert*, by means of an interface that is provided for each type of object.

Consulted expert modules will take into account the information that was added by the human expert (or by other modules). Moreover, the interface to the human expert allows him/her to verify, accept or alter the information generated by an expert module, at any time.

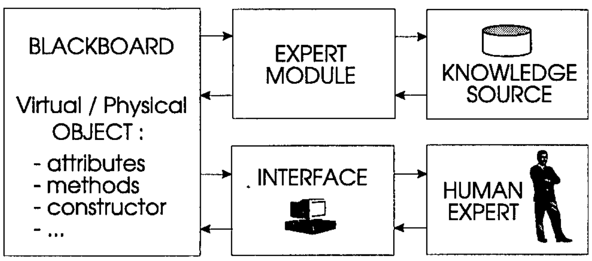


Figure 1. Object-oriented data model for blackboard systems

Objects with partial information (empty attributes, attributes that describe parameter intervals or constraints or multiple discrete values rather than a fixed value,...) will be called *virtual objects*, while objects that are unambiguously determined by the information contained in their attributes will be called *physical objects*.

An object-oriented model for the developed Blackboard CAPP system

This paragraph illustrates how manufacturing data and knowledge have been incorporated in the CAPP system. The following data models are distinguished (figure 2) :

The blackboard. The CAPP blackboard contains both part and process planning information in various states during the process plan generation. The part description can be considered as the initial input data (see metaphor). From this input, new blackboard objects are created by expert modules or by the human operator.

A part model. The CAPP kernel is feature-based. Consequently, the part information, which serves as input to the CAPP system, should a/o contain a detailed description of the part's features. This model incorporates a/o company specific feature types.

A resource model. The resource model embeds machine tools, fixtures, tools, and other auxiliary equipment, available in the factory and considered during process planning. It includes all data that are important to inquire about during the process planning task (e.g. power, accuracy, outer dimensions, axis data, etc.).

A process model. This model contains the manufacturing processes that are used in the company (e.g. end-milling, face-turning, welding, laser-cutting, wire-EDM, etc.). Further, it embeds related process parameters (cutting conditions, costs, accuracy, etc.), and associated geometric constraints and technical parameters (roughness,...).

A process plan model. The blackboard CAPP system supports graph-based process plans that allow the modelling of alternative manufacturing sequences. Such process plans with alternatives are called non-linear process plans or NLPP's.[8] All process plan data that are required for further order processing, manufacturing and all administrative data are included in the model. The process plan model contains the newly generated process plans (in NLPP format) of specific parts.

The outlined data classes are not just some isolated data structure but are interdependent and related to one another by some specific constructs. The manufacturing knowledge in a CAPP system holds the following relationships (figure 2) :

- The 'design related manufacturing knowledge' is employed for instance by the 'CAD expert' module, which allows to extract/add process planning information from/to the part design.
- The 'part-process manufacturing knowledge' associates the data content of the part model to the process model; it embodies the 'process selection expert' module which determines the different manufacturing steps to be undertaken on a certain part type or feature type (modelled in a Generic Petri Net or GPN), and the sequencing relationships between those manufacturing steps. The use of GPNs is explained in the next section.

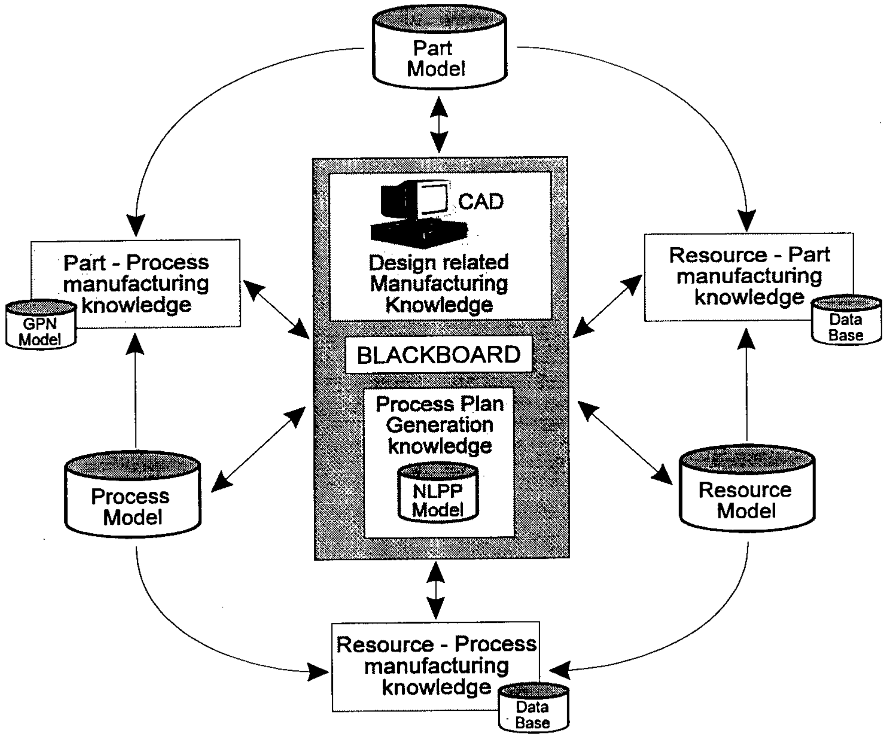


Figure 2. Data models and manufacturing knowledge for CAPP system.

- The 'resource-process manufacturing knowledge' associates the data of available resources to the process model; it embodies for instance the 'machine selection expert' which determines the candidate machine tools for the operations on a certain workpiece. However, this expert module will also have to consult the 'resource-part manufacturing knowledge' (e.g. because there are limitations on part dimensions for a certain machine tool). It can be modelled by means of tables in a data base.
- The 'resource-part manufacturing knowledge' relates the part data with the resource data (e.g. the selection of a tool is influenced by the dimensions of the feature to be processed). This type of knowledge is consulted by for instance the 'tool selection expert' and the 'machine selection expert' modules, and can be modelled with tables in a data base.
- The 'process plan generation knowledge' encloses the knowledge that brings all other knowledge sources together. In this interactive CAPP kernel, the 'blackboard manager' that triggers the distinct process planning expert modules could be considered as part of this knowledge.

In figure 2, the 'data and knowledge loop' around the blackboard can be considered as the generic data and knowledge that is used to build a process plan for any given part. In contrast, the data residing on the blackboard, always refers to a specific part instance.

Generating a process plan requires the analysis of relevant part information, the selection of the right manufacturing processes and the appropriate resources thus building the objects on the CAPP blackboard. The following section elaborates on how the information of each blackboard data-object is supplied by triggering the different expert modules.

Knowledge sources for Blackboard CAPP

This section elaborates on the distinct knowledge sources (figure 2) and their relation with the different data models. It explains for each knowledge source :

- the *knowledge representation* : its content and how it is stored
- the *knowledge instantiation* : how to supply the information contained in each blackboard data-

object (by expert modules or by human interaction)

- the aspect *virtual vs. physical object* : each object created on the blackboard is considered as a virtual object as long as some of its attributes remain unknown; when all attributes are determined, the virtual blackboard objects has evolved towards a physical one.

Design related manufacturing knowledge

This knowledge source provides a link between the CAD model and the manufacturing practices (figure 2). It embodies a/o the 'CAD expert' module. This module allows to extract/add process planning information from/to the part design. Also the 'set-up expert' module uses this knowledge to visualise information like set-ups, operation sequences, etc. on the CAD drawing. These expert modules are explained hereafter and their function is illustrated through some examples.

CAPP oriented part information extraction

Knowledge representation. In this era of CAD systems, it would be advantageous to use the part specification, which is stored in a CAD database, for CAPP purposes. Therefore, the CAPP kernel is provided with a CAD application program that serves as a link to several wire-frame and feature based CAD systems (Applicon Bravo, AutoCad, Unigraphics). This CAD interface can be considered as the 'CAD expert' module. The module supports the human process planner with analysing the geometric and technological information on the part drawing and extracts all part information that is relevant for the feature based process planning system (overall part data, feature data and feature relation data). The design related manufacturing knowledge is thus residing in the CAD drawing itself and in the implementation of the CAD expert module that can interpret this drawing.

Knowledge instantiation. According to the object-oriented blackboard model, explained previously, there are basically two ways to generate the part information (as objects on the blackboard) :

- Manual editing : The complete part description (part, features and feature relations, with

```
WORKPIECE D5641256A (CARRIER)
{
 last_update      = "23.06.1996";
 last_upd_author = cad_capp;
 last_upd_module= "CAD EXPERT";
 WORKPIECE_DATA
 {
  LENGTH        = 60.000;
  WIDTH         = 60.000;
  HEIGHT        = 20.000;
 }
 FEATURES
 {
  hole_1          (DEEP_THROUGH_HOLE)
  {FEATURE_DATA
   {DIAMETER              = 10.000;
    DIAM_STRING_TOL = H7;
    DIAM_UPPER_TOL  = 0.015;
    DIAM_LOWER_TOL  = 0.000;
    LENGTH               = 60.000;
    ROUGHNESS          = 1.600;
    VOLUME               = 4710.000;}
   LOCATED_FEATURES
   {1
    {POSITION
     {10.000, 0.000, 12.500}
     ORIENTATION
     {0.000, 1.000, 0.000,
      0.000, 0.000, 1.000,
      1.000, 0.000, 0.000}}}}
...
```

```
...
  ext_b_pocket  (EXTERNAL_BLIND_POCKET)
  {FEATURE_DATA
   {LENGTH                  = 40.000;
    WIDTH                   = 32.000;
    WIDTH_UPPER_TOL = 0.100;
    WIDTH_LOWER_TOL= 0.050;
    ...
...
 RELATIONS
 {
  1  (PERPENDICULARITY_TOL)
  {object                     = hole_1;
   object_instance_id      = 1;
   reference                  = ext_b_pocket;
   reference_instance_id = 13;
   RELATION_DATA
   { TOL_VALUE             = 0.010;
     TOL_ZONE              = LINEAR;}}
  2  (NEIGHBOUR_RELATION)
  {object                     = ext_b_pocket;
   object_instance_id      = 13;
   reference                  = hole_1;
   reference_instance_id = 1;
   RELATION_DATA
   { WALL_THICKNESS  = 0.500;}}
...
}}}
```

Figure 3. Part information extracted by the 'CAD expert' module

corresponding parameters) can be entered by means of appropriate user interfaces, either via the CAD system or directly on the blackboard (e.g. if no CAD system is available).

- Expert consultation : The 'CAD expert' module transfers the part design from CAD to objects on the blackboard. However, some human interaction is required, before the module can generate a complete process planning oriented part description. This interaction consists of identifying the features interactively by selecting their geometry and associating it with the corresponding user defined feature type. When a feature is identified, the module can automatically inquire its geometric and technological parameters from the CAD database. Feature relations must be defined explicitly, as most commercial CAD systems do not explicitly model relations between features in their native database. Form and location tolerances, which also result in feature relations, are automatically recognised if contained in the CAD database.[9]

Figure 3 shows an example of the type of information that the 'CAD expert' module extracts from the CAD model. It illustrates how a part, its features and feature relations are specified. This information is placed in a part description file that can be inspected by the human operator, and which is translated by the CAD expert module into objects on the blackboard. To provide flexibility, the information gathered by the CAD expert module can always be manually changed or completed by the human operator.

Virtual vs. physical design objects. The part information is transformed into new objects (part, features and feature relations) on the blackboard. During the process of completing the information contained in these objects, virtual objects can be transformed to physical ones. To explain this concept, the case of a feature is considered as an example. A feature will evolve towards a physical object as more characteristics (parameters) of the instance of this type of feature are known. If for instance the corner radius of a pocket may range between 5 mm and 20 mm (e.g. because this parameter is not important for the feature's functionality), a wide range of tools may be valid to produce this feature. When the actual, tool is chosen, the actual radius will be determined.

Selection, visualisation and simulation of possible set-ups

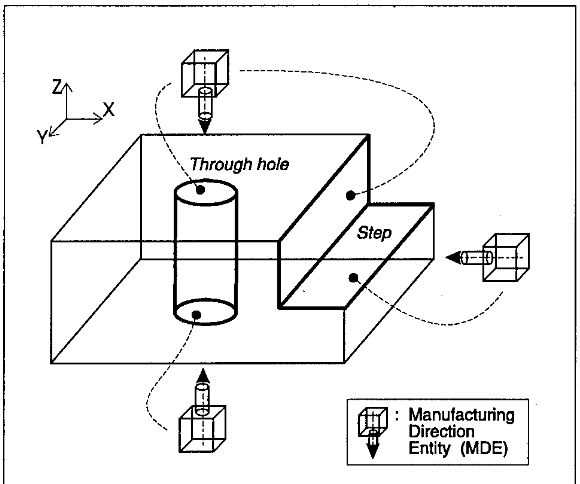
Knowledge representation. The 'set-up expert' module takes 'manufacturing elements' as input. Each manufacturing element holds one or more 'manufacturing direction entities' (MDE). MDEs model the possible orientations of the tool with respect to the manufacturing element. A manufacturing element can be a 'feature' or an 'operation'.

In the first case (feature level), the manufacturing elements are a set of features and a machine tool on which to process the given features. The machine tool can be physical or virtual, depending on the level of information yet available on the blackboard; at least the kinematics of the machine should be known. The search algorithm of the set-up selection expert calculates the most economic number of set-ups, taking into account the machine-tool kinematics, the feature MDEs and possible constraints (e.g. due to feature tolerance relations).

In the second case (operation level), the manufacturing element is an operation; i.e. an aggregation of processes executed on one machine tool. Each process refers to a certain feature and inherits the MDEs from this feature. Again, the set-up expert module will calculate the most economic set-up plan for this group of processes, by means of the same algorithm.

The operation level approach will apply if operations have been selected prior to invoking the set-up module (i.e. selected operations are found on the blackboard). If no or insufficient operation data is available on the blackboard, the set-up selection module will automatically base its decisions on feature information.

Figure 4 summarises both approaches : in this example the MDEs indicate that the through hole can be drilled from +Z and -Z direction, while the step can be milled from -Z and -X direction. When features are used for set-up planning, the actual processes on those features are not yet known. They are however restricted by the MDEs of each feature. For example, the MDEs related to the step in figure 4 allow end-milling form the -X direction or peripheral milling from -Z direction.



Manufacturing element : Feature	Manufacturing element : Operation
Input : - features : *Through hole, Step* - machine (e.g. 3-axis mach.centre) *Output :* 1 Set-up - make Step - make Through hole	*Input :* - operation (i.e. set of processes) : - (Mill, Grind) Step - (Centre Drill, Rough Drill, Bore) Through hole - machine (e.g. 3-axis mach.centre) *Output :* 1 Set-up - Centre Drill Through hole - Rough Drill Through hole - Mill Step - Bore Through hole - Grind Step

Figure 4. Set-up planning schemes

Knowledge instantiation. The instantiation deals with the actual creation of a set-up plan for a given set of features or for a set of processes in an operation. Set-up planning can be performed manually or through consulting an expert :

- Manual editing : On the CAD drawing, the operator can indicate the features to be processed in one set-up. Also reference features or clamping surfaces can be interactively identified on the drawing. The appropriate attributes (e.g. referring to a certain set-up id, or indicating that it is a reference feature, etc.) are automatically created and attached to these features.

- Expert consultation : The 'set-up expert' module, reads the type of machines (e.g. 3, 4½, or 5 axis) from the blackboard. From the CAD drawing, the module gathers all MDEs and the position and orientation of the features w.r.t. the part.[10,11] With this information, the expert module calculates the set-up plan. For each set-up in the plan, the expert module indicates (1) which features are to be manufactured in this set-up; (2) the so called "optional features", which can be executed in this set-up or others; and (3) the positioning features (e.g. datum plane that is milled formerly in another set-up). Each set-up is visualised on the CAD screen by giving the different feature groups a specific colour. Further the module draws a symbolic representation of how the part should be clamped on the machine.

When the manufacturing element is an operation, the processes are extracted from this operation. The set-up plan for the given collection of processes is calculated using the same algorithm (see also figure 4). Visualisation in the CAD screen is done by colouring the features on which the processes are performed.

Virtual vs. physical set-ups. There are four cases where the set-up can be considered as a virtual object on the blackboard :

- there exist optional features that still can be appointed to another set-up

- the design is still incomplete, and newly added features could be added to this set-up

- the planning is done only on feature level, not on process level.

- the fixture has not yet been designed/selected; note that one fixture can contain multiple (virtual) set-ups.

Part-process manufacturing knowledge

This knowledge relates the data content of the workpiece model to the process model. It is consulted mainly by the 'process selection expert' which determines the different manufacturing steps to be undertaken for a certain workpiece or feature, and the sequencing relationships between those manufacturing steps.

Knowledge representation. The CAPP kernel uses the concept of 'generic Petri nets' (GPNs) as a tool to model the manufacturing knowledge for **part types** (families) and **feature types**, which enables the CAPP kernel to support variant, generative and hybrid planning modes.[2,12] A generic Petri net represents company specific knowledge, structured in a graph, that describes all possible process routings for all conceivable instances of a specific feature type or workpiece type.

A part related GPN models processes that could typically be executed on that specific type of part, like 'saw from stock', 'final inspection', 'paint', 'electrolytic treatment', etc. A feature related GPN outlines the particular processes that could be performed on the feature type at hand (e.g. 'centre drill', 'die sink EDM', 'bore', 'hone', etc.).

In the example of the feature type GPN in figure 5, each rectangular block is a possible manufacturing step that is linked to a process from the process model.

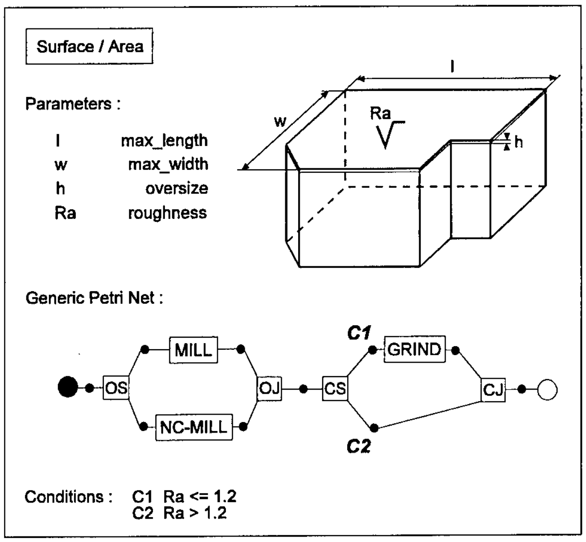


Figure 5. Example Generic Petri Net (GPN) for a 'Surface'

GPNs generally provide manufacturing alternatives by *or-splits* (OS), *or-joins* (OJ), *conditional-splits* (CS) and *conditional-joins* (CJ). While an OS refers to alternatives that are valid under all circumstances, a branch succeeding a CS models a valid alternative only if the condition related to this branch is obeyed.

Knowledge instantiation. Like any other information on the blackboard, the processes to be executed on a given part, can be entered manually or retrieved from an expert module.

- Manual editing : The CAPP kernel offers a graphical editor (figure 6) that allows the operator to define a set (branched graph or sequence) of company specific manufacturing processes to be performed on the part or on its features. Moreover, process graphs or sequences of similar parts or features can be loaded into the editor. These graphs/sequences can still be edited according to the specific instance of the feature or part at hand (e.g. add or delete a specific process or a complete alternative branch).

- Expert consultation : The 'process selection expert' module analyses the type of part and the associated feature types and retrieves the corresponding part and feature GPNs from the process model database. The module generates the *part-process knowledge* for the part and feature instances at hand, by 'evaluating' their GPNs. The process selection expert module does this by removing all branches after a conditional split (CS) for which the conditions do not meet the actual part or feature parameters (e.g. dimensions, roughness, etc.). An evaluated GPN contains no more conditional elements. It is not generic anymore, but only valid for the feature or part instance at hand. At this stage it is simply called a Petri net (PN). The resulting PN can be visualised by a graphical editor (figure 6). If the part-process manufacturing knowledge is incomplete, the user can still edit the result returned by the expert module.

Virtual vs. physical processes. The Petri nets only model the process types and sequences; no resource information is associated to the processes at this stage. Until all process parameters are determined, the process (created as an object on the blackboard) remains virtual. These parameters highly depend on the selected resources (machine, tool and fixture). When the resources are selected, the process parameters (e.g. spindle speed, feed rate, cutting force for milling, laser-power for laser cutting, etc.) can be calculated.

Resource related manufacturing knowledge

Resource related knowledge sources are consulted by different experts : the 'machine selection expert', the 'tool selection expert', the 'fixture selection expert',.... If an expert module tries to find a resource for a given process (e.g. a tool for deep-drilling), it will also have to take the part information into account (e.g. hole diameter, length, roughness,...). Another example : the selection of a resource (e.g. a fixture) for a given part will be influenced by the process parameters (e.g. the cutting force during turning). Therefore, the resource related manufacturing knowledge comprises both the resource-part and the resource-process related knowledge, explained here in this section.

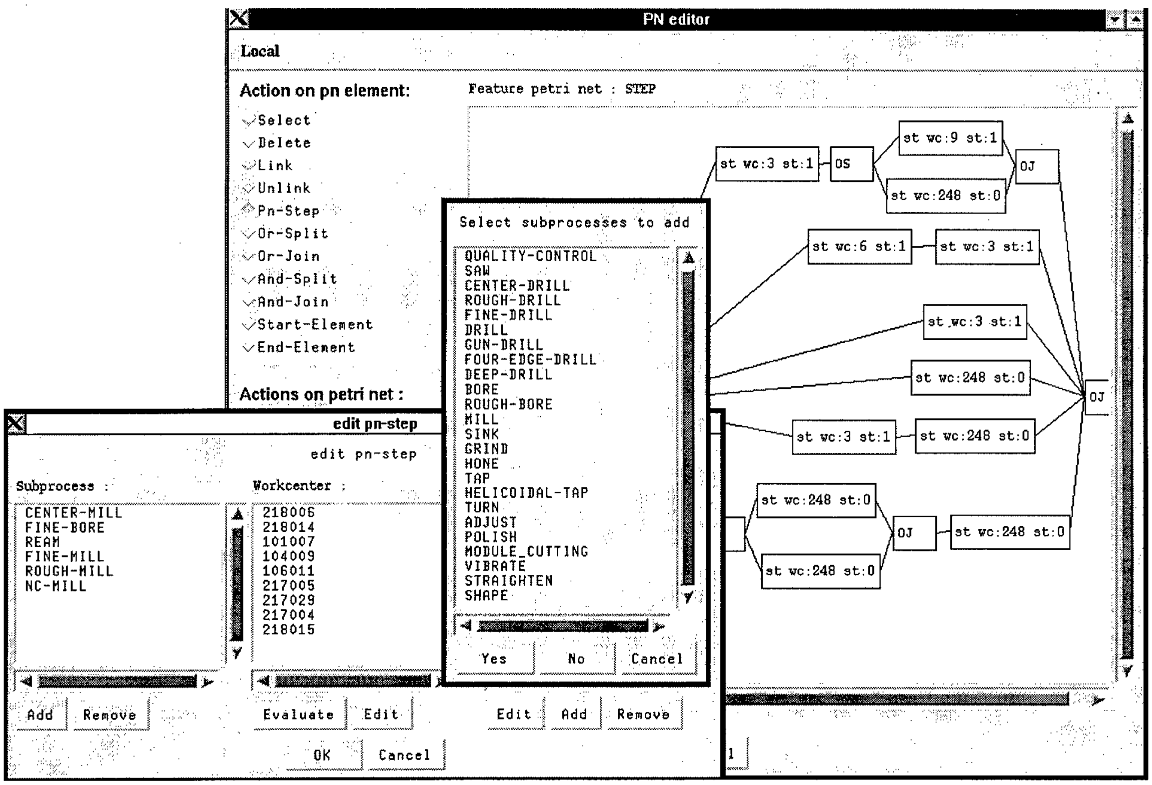


Figure 6. The graphical editor for modelling part-process knowledge

Knowledge representation. Resources are modelled using tables in a relational database. Resource related knowledge is structured through links between these tables and other tables, delineating the capabilities of the resources. A machine tool for instance does not only refer to its parameters, statistical data (e.g. mean lead time, operation time, set-up time, etc.), axis data, etc. but also to feature and workpiece parameters that impose boundary conditions : i.e. a machine tool is capable of executing a process on a feature or part whose parameters (e.g. length, tolerance, roughness, etc.) are within the specified bounds.

Knowledge instantiation (The machine selection expert). The relation between the company specific processes and the company's machine tools is described in tables of the relational database. The machine selection expert module can generate standard SQL for executing the proper queries. It will thus return one or more machines that can perform a certain process. However, during the selection of a machine tool the expert module will also take into account the parameters of the part and its features, where necessary (e.g. a milling operation on a heavy part cannot be done on a tiny milling machine). The 'machining capabilities' table models the possibilities of each machine tool and parameter limits for a specific manufacturing process for manufacturing a specific geometry (e.g. maximum diameter for drilling in steel, maximum clamping force for milling, power, maximum spindle torque, maximum dimensions of the clamped part, kinematic range, etc.).[13]

Knowledge instantiation (The fixture selection expert). The selection of a fixture (modular fixture, standard vice, calibre,...) strongly depends on :

- the type of process : e.g. a chuck for turning or a modular fixture for milling
- the kinematics and dynamics of the machine : controllability, reachability, and accuracy of the distinct axes, the clamping facilities (vice, pallet exchange device, etc.).
- the geometric part data : e.g. positioning and clamping points, geometry to manufacture, machining direction, weight, etc.
- the number of set-ups, returned by the set-up selection module : e.g. a fixture or pallet can comprise two or more set-ups (rotation-table).

For machining of prismatic parts, a fixture selection expert module is developed that uses this information for determining the components of a modular clamping device.[10]

Knowledge instantiation (The tool selection expert). This expert module is incorporated in the commercial P2G system that is linked with the developed CAPP kernel.[14] The module selects tools for a given process that is executed on the part or on one of the part's features. Naturally, geometric and technological part information is of vital importance during this process. Some examples :

- the radius of a face mill must be smaller than the corner radius of the pocket that has to be milled
- if a hole has a roundness tolerance of 0.01 mm, a twist drill will not deliver the required result, instead a reamer or bore will have to be used during the 'hole making' process.

The selection is made from a standard or a customer tool catalogue, taking into account the part and feature parameters. If the tool is chosen, the module calculates the most economic process parameters based on Kienzle's law for cutting forces and Taylor's law for tool life time. Note that new types of processes may require new experts : an in-house developed software for selecting the appropriate process conditions for EDM could be a complementary expert to some commercially available expert system for calculating metal cutting parameters.[15]

Virtual vs. physical resources. A resource remains a virtual blackboard object until it is unambiguously described by its parameters (i.e. only one single tool can be appointed). When a machine tool is described by characteristics like : numerical controlled, 4½ axis, possible processes, etc., a query for a suited machine will probably result in an enumeration of possible candidates. When one machine is selected from this list, the resource becomes a physical object on the blackboard.

Process plan generation knowledge

Knowledge representation. In the developed CAPP kernel, the process plan generation knowledge consists of a Petri net based search algorithm and the 'blackboard manager' that triggers the distinct process planning expert modules (process selection, machine tool selection, fixture selection, etc.). The ways of managing a blackboard system has been described previously. As stated there, the user driven approach for managing a blackboard is chosen. At any time during the creation of a process plan, the user can invoke an automated module (an expert) for a specific process planning task and inspect or eventually change the returned results.

During the generation of the process plan, the objects (features, processes, machines, fixtures, set-ups, feature relations, etc. residing on the blackboard) become part of the process plan generation knowledge/data.

Knowledge instantiation. By triggering the expert modules or by manual editing, several blackboard objects are created. At some time, these objects will all have to fit into the non-linear process plan that is being generated. Because of the high flexibility of plan generations one can expect many scenarios for finalising the process plan. Again, the concepts of manual editing and expert consultation are important to mention within this context. They are shortly explained hereafter.

- Manual editing : Graphical editors for each planning task (e.g. figure 6) allow for the interactive construction of process plans. Plans can be built up *form scratch* or through *similarity planning* (group technology oriented). In the latter case the resembling plan is loaded from a file or database and manually changed according to the specifications of the part at hand.
- Expert consultation : The 'process sequencing expert' generates a graph of operations (i.e. the NLPP) through performing a search. Part and feature Petri nets (PNs) and the assigned machine tools form the input for the expert module. A number of techniques have been implemented to ensure high performance of the developed search algorithm :
    - ◊ *Combined variant/generative planning*: The algorithm combines the part related operations (part PN) and all feature related operations (feature PNs) to one non-linear process plan (NLPP). During this search, all feature relations (e.g. tolerance relations, interference relations) are taken into account. These relations are evaluated, resulting in constraints (e.g. grouping or sequencing of operations) which will guide the search for the NLPP.[8]

◊ *Constraint based search* : Apart from the constraints that result from feature relations, planning restrictions coming from the scheduling department can be taken into account (e.g. avoid the use of bottle-neck machine X, create an alternative for machine Y, try to use modular fixture Z, etc.). Such constraints can be generated automatically (e.g. via statistical analysis of workshop data) or entered manually by schedulers.[16]

◊ *Cost based search* : Weight factors can be entered for a number of cost criteria (e.g. number of set-ups, number of conventional tools, number of CNC centres, etc.). Specific search algorithms (e.g. A*, best first, branch & bound) take these factors into account and produce solutions very quickly.[12]

- Opportunistic planning expert : Opportunistic process planning is a new concept in the CAPP (research) domain. The idea is fairly simple and resembles the way human process planners think. The opportunistic search algorithm takes an existing non-linear process plan and a feature Petri net as input, and checks whether the feature can be produced on the already determined sequence of machines (outlined by the NLPP). Opportunistic planning is an effective instrument in many cases :

◊ *Generative planning with large number of features* : When the part consists of many features (>100), this tool becomes very powerful. In this case, the human expert selects the features that will most likely determine the general outlay of the process plan. For these features a NLPP is generated. The other features are added to the NLPP afterwards using the opportunistic search algorithm.[2]

◊ *Similarity planning* : The user retrieves an existing process plan for a part family. Features that make up the specific differences of the part at hand are fitted into the process plan.

◊ *Design For Manufacturing* : A process plan is generated at an early stage of the design. When new features are added to the design, an on-line checking whether the feature can be made on the selected machines, can be performed.

Virtual vs. physical process plan. The NLPP is an aggregation of objects. The NLPP - as one object on its own - is a physical blackboard object if all its components are fully defined (i.e. they are physical too).

CONCLUSION

The manufacturing knowledge, contained in the CAPP system described in this paper, is very diverse. It relates the object classes : workpiece-families, workpiece, features, relations, processes, generic Petri nets, manufacturing direction entities, rules, rule-bases, machines, machine capabilities and various knowledge sources into one common object-oriented model. This model is dynamically instantiated, stepwise built up by relating one or more types of objects together to create new objects. This complex generation mechanism increases the potential to represent manufacturing knowledge in the way humans reason. Moreover, the developed CAPP system is based on a blackboard architecture : several expert modules can be triggered in an arbitrary order to perform a specific planning task, ensuring a very flexible way of performing the CAPP activities. Solutions generated by the assisting expert modules result in objects on the blackboard. These solutions can be adjusted or overruled by the operator, since each blackboard object has an interface to the human expert for manually adding or changing the information residing in the objects. Even more flexibility is obtained by introducing opportunistic process planning, where feature process plans are fitted onto an existing NLPP. The CAPP kernel described in this document, offers the user full control over all separate planning activities as the process plan is being finalised.

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Joint Strike Fighter Manufacturing Demonstration (JMD)

"Integrating Design and Cost for an Affordable Weapon System"

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USA

Summary

In 1995, the Joint Strike Fighter (JSF) program office, through the USAF Wright Laboratory's Manufacturing Directorate, contracted with Hughes Aircraft Company to define and demonstrate a development methodology that incorporates lean practices and tools and integrates design and cost information. This methodology will be refined, demonstrated and shared with the JSF contractor community. The JMD program is a 40-month effort in two phases. The first phase (Aug 95-Jan 97) developed the initial JMD lean methodology and demonstrated its application to a Transmit/ Receive microwave electronic module used in active array radars. The second phase (Jan 97-Nov 98) will refine the methodology and demonstrate it on a more complex subarray assembly. This paper describes the JMD program and presents its progress to date.

Background

The JSF is developing a family of tactical aircraft to meet the next generation strike mission needs of the US Navy, Marines, Air Force, and Allied Forces. The cornerstone of this program is affordability. With this in mind, the JSF program has been a leader in affordability activities such as the Lean Aircraft Initiative (LAI).

Modeled after the Massachusetts Institute of Technology's International Motor Vehicle Program, the LAI is a joint US Air Force - Industry effort to identify key principles and practices which will enable the implementation of lean manufacturing within the US aerospace industrial base.

LAI surveyed its members and found that those companies who had database commonality among design and cost information achieved significantly better

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schedule and cost performance than those who did not. The results of this survey appear in Figure 1.[1]

LEAN Finding

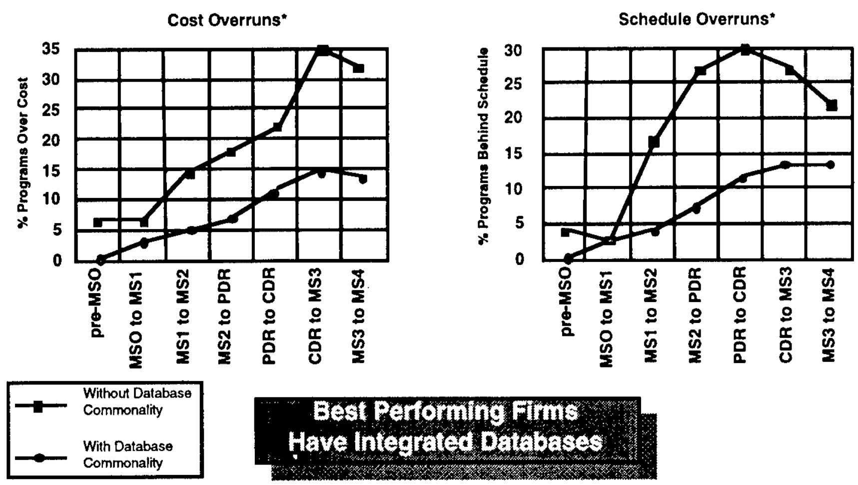


Figure 1. Integrated Cost/Design Databases Correlate with Program Performance

As part of its research, the LAI identified the following attributes of an integrated cost/design database:

- Makes cost readily accessible to the design team
- Tailors application to fit Integrated Product Team (IPT) scope
- Maximizes use of actual cost data - minimizes dependence on cost models
- Cost data kept very current
- Cost impact of design changes can be determined at the micro (parts/assemblies) level
- Rolls up product costs frequently.

Three Part Methodology

To achieve these goals, the JMD team developed a three part methodology consisting of:

- an all-tier product development process keenly focused on meeting all customer requirements,
- a number of corporate strategies including design to cost, activity based management allowing for improved cost visibility, team motivation, and strategic sourcing and supplier development, and
- software support tools that integrate design and cost information enabling near-real time cost estimation and simplified knowledge base development.

The JMD methodology is depicted in Figure 2. Each part of the methodology will now be discussed.

JMD Methodology

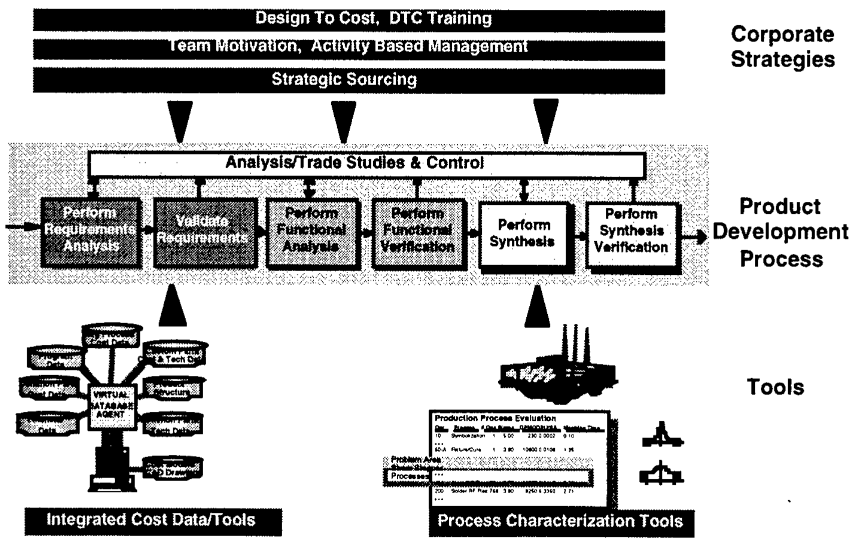


Figure 2. The JMD Three-part Methodology

Product Development Process
The product development process (PDP) developed by Hughes Aircraft Company provides a consistent format and terminology necessary to flow down common objectives and metrics to performing integrated product teams (IPTs). The PDP also defines the general data content of integrated databases that are key to product development. The PDP is accomplished at each level of the product hierarchy (system, subsystem, assembly, component etc.) and repeated for each phase and subphase of a development (concept development - preliminary design etc.). At each level the PDP describes the "what" and "who" of each design activity using process maps and activity sheets (i.e., what are the inputs, what are the activities performed, who are the responsible participants for executing the activities, and what are the outputs resulting from the process step). An example of this hierarchical structure appears in Figure 3.

To develop a best value design for the customer, an IPT using this process begins with customer requirements and follows a standardized iterative process to balance competing requirements, identify lower level requirements, and feed results to higher level analyses as required. This is repeated until the optimum solution for the customer has been identified and developed.

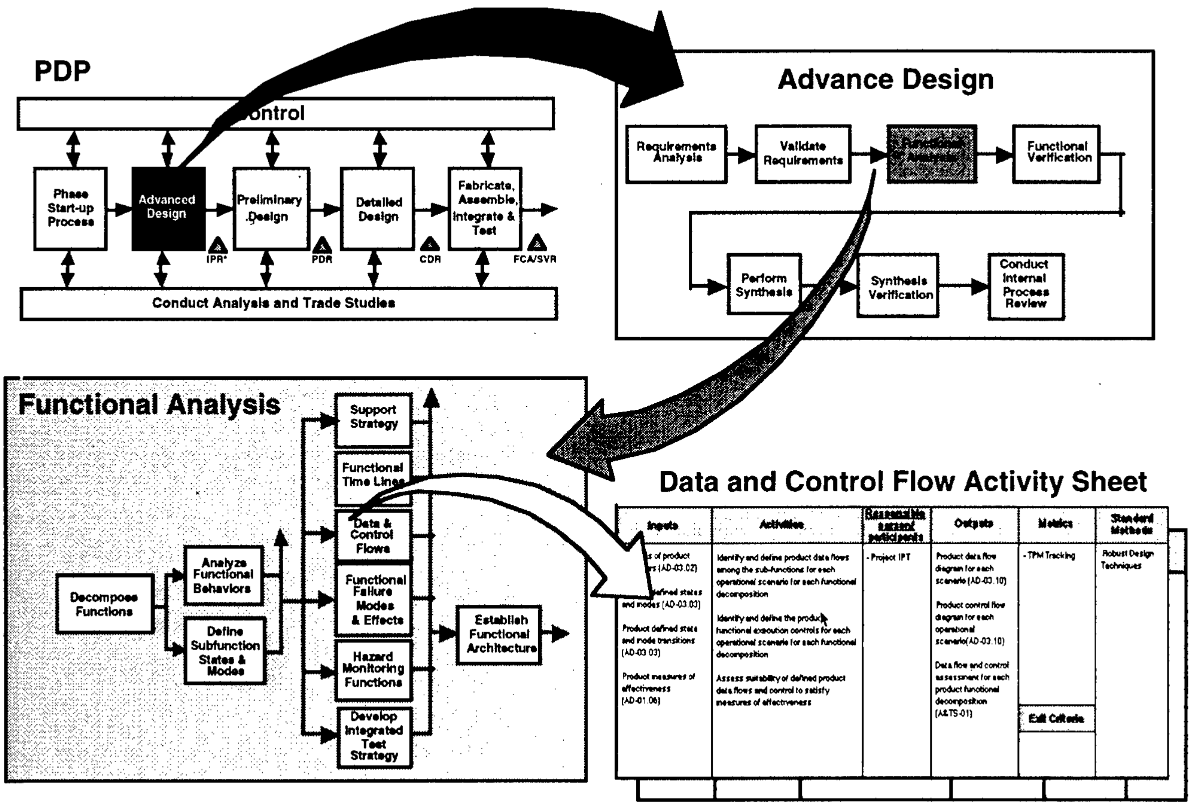


Figure 3. PDP Documentation is Hierarchical Consisting of "Maps" and "Activity Sheets"

While this particular version of PDP is not required for JMD (other companies will have their own), it does provide context for the JMD process and tools. Key points to look for in assessing a product development process are:[2]

- Customer driven
- Disciplined
- Supports all levels of decomposition and development phase
- Not product specific
- Iterative
- Provides insight to higher level assessments and lower level requirements
- Enables IPT members from several disciplines to work together to develop a balanced, best value design for the customer

Corporate Strategies

JMD has identified four corporate strategies which are critical to developing affordable and capable products: Design to Cost (DTC), Activity Based Management (ABM), Team Motivation, and Strategic Sourcing.

Design to Cost (DTC)[3]

Design to Cost establishes a cost culture wherein cost is treated as a critical and independent variable. Traditionally a standalone activity, DTC has become an integral part of the product development process. It permeates the development environment and dominates all major design decisions. To ensure best customer value, PDP activities are iterated to achieve affordable designs and are executed at each level of the product breakdown structure. The iterative

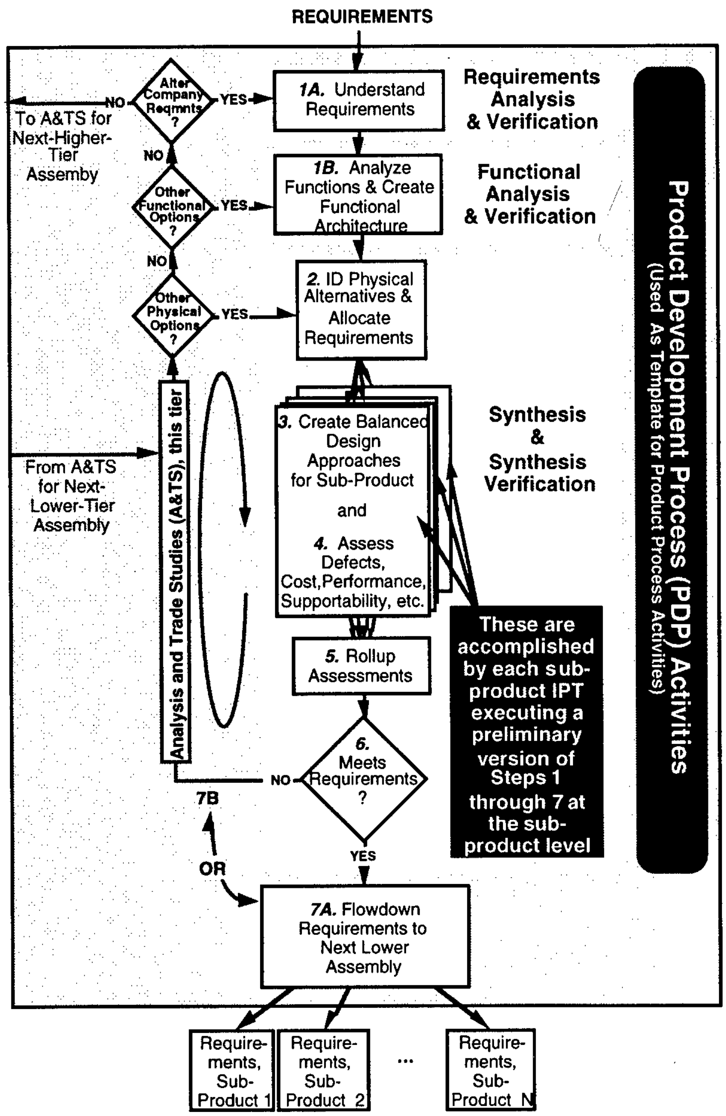


Figure 4. Seven Steps to an Affordable Design

seven-step DTC process is summarized in Figure 4.

Key DTC requirements include:

- Cost must be an independent design requirement with importance equal to or greater than performance (i.e. the process must address Cost As an Independent Variable as its primary focus or CAIV).
- DTC must begin as early as possible in a program to enable early cost driver identification.
- Lean practices and processes must be effectively leveraged.
- Cost estimation cycle time must be near-real time by the detailed design phase.

- Design, manufacturing, and cost data must be readily accessible to the Integrated Product Team (IPT).
- DTC tools must be user friendly and accessible at the IPT's desktop.
- Manufacturing process costs must be well understood.
- DTC training, deployment and data collection must be given a high priority.

The JMD methodology enables the achievement of each of these requirements.

ABM Implementation

Planning Phase
- Select the project target area
- Select the project team
- Define the project scope
- Educate the team

Activity Analysis Phase
- Understand the existing cost structure
- Identify the operation's activities
- Mapping the operation's cost to the operation's activities
- Identify the activity drivers

Cost Analysis Phase
- Review Activity/Cost matrix
- Identify and eliminate non-value activities

On-Line Activity Based Management
- Align the cost collection structure to activities
- Establish system to collect activity counts
- Integrate the activity costs and activity counts

Figure 5. Top-Level ABM Implementation Methodology

Activity Based Management (ABM)[4]

Since a key requirement of JMD is to make cost data readily accessible to the design team, it is important that the cost data be accurate and current, particularly product and process costs. One method of gaining insight into product/process costs is Activity Based Management (ABM) / Activity Based Costing (ABC).

Traditional accounting methods start from a paradigm which says that organizations consume resources and programs use organizations' resources. ABM and ABC use a different way of viewing resource consumption. Namely, activities consume resources and products consume activities.

One weakness of traditional methods is that the true cost of a product may be masked by allocated support and overhead costs. In ABM/ABC, overhead and allocated support costs are mapped directly to the activities they support. This enables a company to better understand how and where its resources are being used, identify non-value added activities, and reduce costs.

The JMD program has initiated the application of ABM at the Hughes Electronics Microwave (HEM) facility in Tucson, Arizona to improve cost visibility of Transmit/Receive electronic modules. During 1996 a small pilot application was conducted at HEM to test the implementation of ABM. Based on its success, we plan to use activity based cost information coupled with process characterization data to support the near - real-time cost analysis for the more complex subarray, which is the focus for the JMD Full Demonstration in November 1998.

A top-level methodology for implementing an ABM project can be organized into four phases: planning, activity analysis, cost analysis, and on-line implementation. This methodology is summarized in Figure 5.

Team Motivation[5]

The effective use of teams is a key part of achieving a lean organization. As part of the JMD effort the literature regarding team motivation and effectiveness was reviewed and a small survey was accomplished. The literature review identified several factors which contributed to team effectiveness. These were grouped into three areas: individual factors (e.g. team members' commitment to the goal, members' valuing diversity of people, skills and disciplines on the team etc.); team factors (e.g. collective knowledge and skills of the team, level of mutual trust, and shared beliefs that the team can succeed etc.) and organizational factors (e.g. team based performance management and appraisal, team recognition and rewards, and team training). The literature also emphasized work or task factors (e.g. variety, complexity, type, challenging vs. routine etc.) but we did not include these in our survey.

A team of Hughes senior managers identified 17 "successful team leaders" who were most likely to "deliver a product on time and within budget , deliver a product that meets quality specifications, establish customer satisfaction and establish team satisfaction." These were then placed in a pair of focus teams and asked a series of questions related to what made some teams successful and others not. The results were highly consistent with the findings in the literature with two exceptions: the participants did not believe team monetary rewards were as important to team success as the literature and that team leader skill, focus and perceived commitment was more important than the literature portrayed.

Strategic Sourcing[6]

Earlier studies have identified that 50-70% of the value of a typical aerospace product is in supplied components and assemblies. As a result, the supply chain must be a key element of any effective

cost reduction activity. Recognizing this, the JMD team reviewed a number of supplier management practices at Hughes for potential application elsewhere. (See figure 6.)

Figure 6. The Hughes Strategic Sourcing Structure is Augmented by Four "Best Practices"

There are three structural elements to strategic sourcing as practiced by Hughes. The first of these is commodity alignment. All parts and purchased materials were divided among four commodity areas (Metallic, Indirect, Chemical, and Electrical or MICE). Each of these areas has a director, who is responsible for this commodity across all business units.

The second element consists of four common practices which were taken from Hughes' parent company - General Motors' Worldwide Purchasing approach: Global Sourcing, Advanced Purchasing, Creativity Teams, and Supplier Development. Global Sourcing is used to identify those suppliers from around the world who can supply the best quality, service and price for existing designs where qualification activities and production implementation have already been accomplished. Advanced Purchasing is a process used to identify strategic suppliers and bring them into a design IPT to help ensure early design decisions incorporate supplier capabilities and insights. Creativity Teams are multifunctional

teams focused on a single commodity. They work to rationalize the supplier base for their commodity while meeting the needs of all business units. Supplier Development is chartered to provide material leadership in the deployment of lean business practices such as design to cost, acquisition reform, six sigma, ISO 9000, benchtrending, electronic commerce, supplier improvement workshops, and advanced supplier development.

The third element is the Source Selection Review Board (SSRB). This group consisting of the Executive Director of Worldwide Purchasing; the Material and Commodity Directors; the Director of Supplier Development; Legal and Ethics, Finance and representatives from each of the business units meets every week to review all purchases in excess of $100K and all strategic agreements regardless of size. The SSRB ensures that material goals are met and processes are followed. In addition, the SSRB sponsors creativity teams.

The structural elements above are supported by several key practices. These include the following:

- A standard 0-4 rating system as part of the Hughes Supplier Certification system. A 4.8 sigma level (99.95% defect free) is a minimum criteria for consideration for certification.
- A Six Sigma parts database containing approximately 17,000 parts and parts families along with their sigma data.
- Six Sigma information is now part of every design review. Management review of Cpk information is now routine resulting in increased emphasis and use by the Integrated Product Teams.
- Training is provided in Six Sigma and Worldwide Purchasing to IPTs, managers and suppliers.

JMD Support Tools

There are two sets of support tools which have been developed by the JMD program: the process characterization toolset and the integrated design cost database tools.

Process Characterization[7]

Fully understanding the manufacturing process: its flow, material , manpower , equipment requirements, and possible unscheduled tasks (such as rework), is the focus of process characterization. Process characterization provides the information needed for cost/yield estimation and for identification of process improvements that will lower costs and defects while increasing capability and efficiency.

The JMD team has developed a toolset to enable the efficient characterization of manufacturing processes. This toolset consists of five commercial-off-the-shelf (COTS) software packages: SilverRun from SilverRun Inc. ,Ingress' Database Management System and Windows4GL , Graphical Query Language (GQL), and SAS' JMP statistical analysis package. The relationship among these tools is summarized in Figure 7.

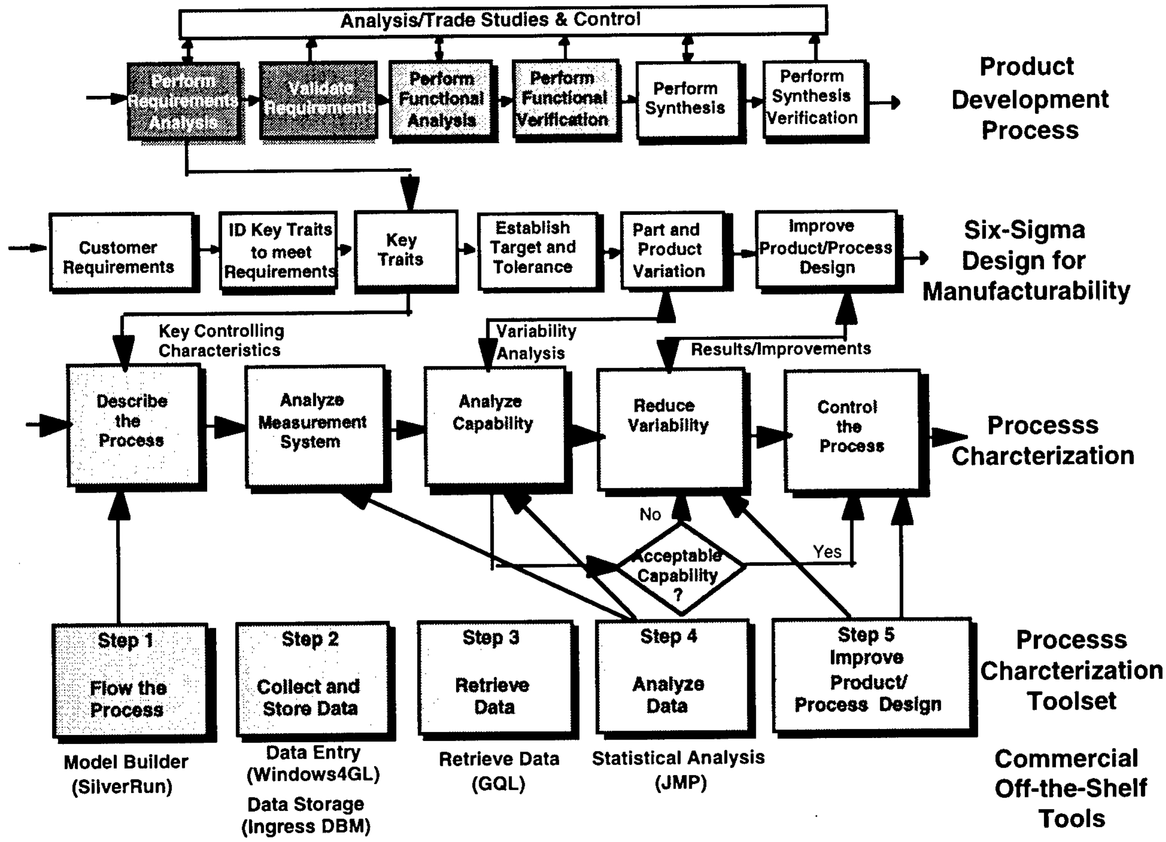


Figure 7. Relationship Among
DTC, Six Sigma, and the Process Characterization Methodology and Toolset

These tools have been used to characterize processes at the Hughes Electronics Microwave facility in Tucson, Arizona to support the JMD subarray demonstration. The output of the Process Characterization Toolset will be made available to the design IPT through the JMD integrated design/cost environment.

Cost/Design Data Integration Tools

The integration of design and cost data, and making this data available to the design IPT in near-real time, is the heart of the JMD program. In order to achieve the attributes/requirements identified by the Lean Aircraft Initiative above, the JMD team selected a number of commercial-off-the-shelf (COTS) tools to accomplish its initial integration and demonstration. After refining the data requirements with the T/R module IPT it was decided that data from each of the Hughes corporate databases shown in figure 8 would be provided to the design team through Cognition Inc.'s Cost Advantage™ cost modeling package.

This integration was initially accomplished through the development of a custom intelligent Virtual Database Agent (VDA). In order to facilitate transfer of this methodolgy to the JSF community, the team is upgrading the VDA with commercially available, industry standard, Common Object Request Broker Architecture (CORBA) compliant software.

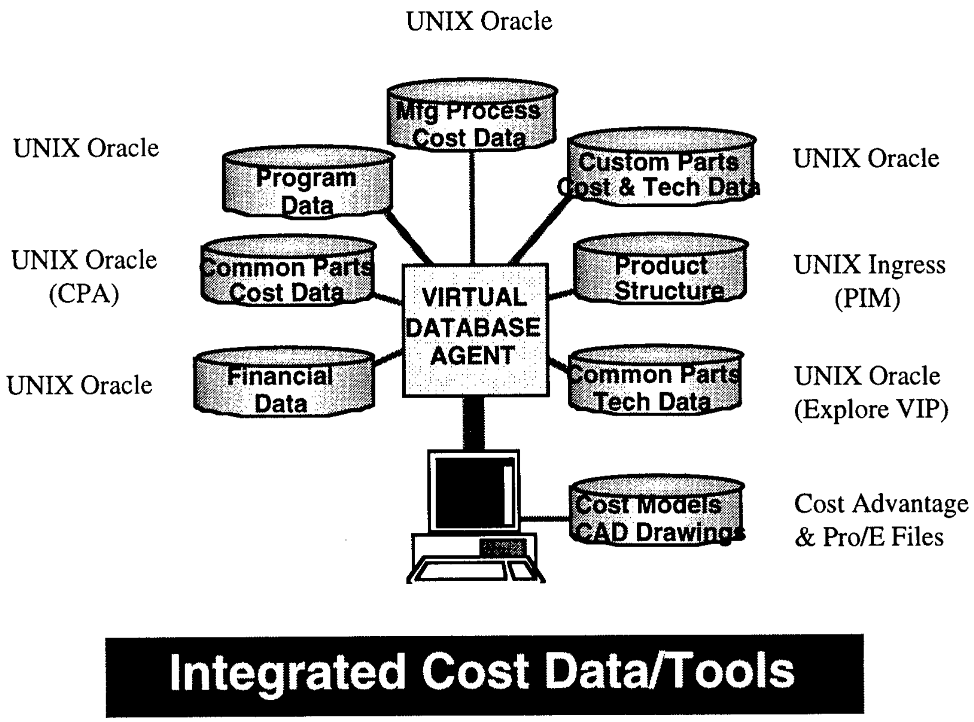
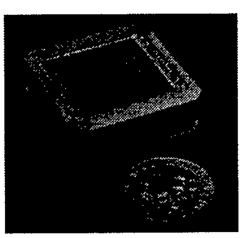


Figure 8. The JMD Integrated Cost/Design Environment

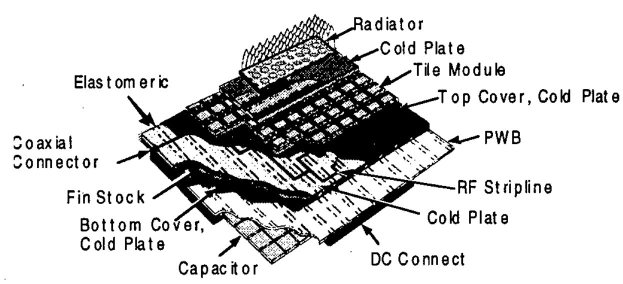
Mini Demonstration
Aug 96 - Jan 97



Transmit/Receive Tile Module

19.3% Cost Reduction (non-MMIC)
60% Reduction cost /perf. tradeoff cycle time
27% Reduction in tradeoff labor hours

Full Demonstration
Aug 98 - Nov 98



Transmit/Receive Tile Subarray

20% Cost Reduction (including MMIC)
60% Reduction cost /perf. tradeoff cycle time

Figure 9. JMD Demonstrations Prove the Effectiveness of the JMD Methodology

Demonstrations

The JMD team successfully demonstrated the effectiveness of the JMD methodology at a demonstration held in January 1997. Using the integrated design/cost environment, the team was able to perform design trades to reduce the cost of Transit/Receive electronic modules by 19.3%. The methodology also showed large reductions in tradeoff cycle time and labor hours. The methodology will be applied to a more complex subarray assembly and demonstrated in November 1998. A summarization of the JMD demonstrations appears in Figure 9.

Next Steps

The next steps for the JMD program are to refine the methodology, complete the transition to CORBA compliant software, conduct the November 1998 scale-up demonstration and transfer the methodology to the JSF community at large. The methodology and results are described in greater detail in a series of reports available through the JSF program office.

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[1] David P. Hoult etal., "Cost Awareness in Design: The Role of Data Commonality", SAE Technical Paper Series: Paper 960008. SAE International. Warrendale, PA. p. 3

[2] JSF Manufacturing Program Design to Cost Guide. Joint Strike Fighter Program Office. 16 Aug 96. p. 1-2

[3] Ibid. p. 2-2

[4] JSF Manufacturing Program Lean Practices and Processes for the IPPD Environment. Joint Strike Fighter Program Office. 25 Jun 97. Section 6.

[5] Ibid. Section 4.

[6] Ibid. Section 5.

[7] JSF Manufacturing Program Process Characterization Toolset Users Manual. Joint Strike Fighter Program Office 25 Jun 97 pp. 4-5.

MULTI-PHYSICS MODELLING - A VITAL COMPONENT OF VIRTUAL MANUFACTURING

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ABSTRACT

One of the core tasks of the virtual manufacturing environment is to characterise the transformation of the state of material during each of the unit processes. This transformation in shape, material properties, etc can only be reliably achieved through the use of models in a simulation context. Unfortunately, many manufacturing processes involve the material being treated in both the liquid and solid state, the trans-formation of which may be achieved by heat transfer and/or electro-magnetic fields. The computational modelling of such processes, involving the interactions amongst various interacting phenomena, is a consider-able challenge. However, it must be addressed effect-ively if Virtual Manufacturing Environments are to become a reality!

This contribution focuses upon one attempt to develop such a multi-physics computational toolkit. The approach uses a single discretisation procedure and provides for direct interaction amongst the component phenomena. The need to exploit parallel high performance hardware is addressed so that simulation elapsed times can be brought within the realms of practicality. Examples of multi-physics modelling in relation to shape casting, and solder joint formation reinforce the motivation for this work.

1. INTRODUCTION

Virtual manufacture really has to be considered in the context of a concurrent engineering environment where the focus is on design for both:

- fitness for purpose
- fitness for manufacture.

The idea of a Virtual Manufacturing Environment, (VME) where information about a complex piece of engineering equipment (eg. an aeroplane) is stored electronically, from the highest conceptual level down to the lowest most detailed component level plus all their possible groupings and interactions, is gradually emerging as a reality. The structural map for the delivery of the virtual factory is essentially in place, and the challenge for the Computer Aided Engineering (CAE) community is to deliver a comprehensive set of mutually compatible software tools that comprehensively address each aspect of the process of design and virtual manufacture. We emphasise the interaction of design for performance and then again for manufacture, because they cannot be easily uncoupled in the task of producing, for example, structural components with high integrity demands.

In the design of structural components, computational modelling has been used extensively for some decades. Frequently, the shape of components is determined to optimise the flow distribution or heat transfer characteristics, and to ensure that the structural performance in service is adequate. From the perspective of computational modelling, these activities are typically separated into:

- fluid flow and the associated heat transfer (possibly with chemical reactions) based upon Computational Fluid Dynamics (CFD) technology
- structural analysis, again possibly with heat transfer, based upon finite element analysis (FEA) techniques.

Until recently, little serious attention has been given to the coupled dynamic fluid-structure interaction 'flutter' problems in the design for operation context. Such problems are conventionally addressed by focusing on one phenomena with the effects of the other represented crudely. The CAE community has tended to focus its attention on either flow or structural mechanics phenomena.

From a computational perspective this is not surprising:

- the Navier Stokes and related equations characterising the flow of fluids have conventionally been solved by finite volume techniques with segregated iterative solvers
- the stress-strain equations are almost exclusively solved using finite element methods traditionally with direct solvers.

Despite the fact that in the last couple of years, a number of workers have shown that the formal mathematical distinctions between finite volume

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and finite element methods are marginal[1], these classes of approach have, in fact, led to modelling software tools which are entirely distinct.

Whilst this focus into distinct CFD and FEA software has served the needs of the design function, it has been less than adequate as far as the modelling of manufacturing processes is concerned. One key reason for this is that most manufacturing processes involve material exhibiting both "fluid" and "solid" mechanics behaviour. Some processes, such as forging and superplastic forming, which involve both 'flow' and 'stress' characteristics can be solved by FEA software using a large deformation formulation and sophisticated contact analysis to represent the surface interactions (see, for example, the NUMIFORM conference series [2]). However, many forming processes involve a change from liquid to solid state via solidification processes; these include shape casting of metals, plastics moulding and composite shape manufacture. To model such processes adequately requires software tools which facilitate the interactions of a range of physical phenomena, which includes fluid and solids as well as electromagnetic field behaviour! Of course, a demand is also emerging for such modelling software tools to analyse the multiphysics aspects of the operational performance of aerospace equipment in service. Unfortunately, it has proved very difficult to solve coupled problems by combining phenomena specific software tools for a whole host of reasons.

2. KEY ISSUES IN THE DESIGN OF MULTI-PHYSICS MODELLING SOFTWARE TOOLS

If modelling software tools are to facilitate the analysis of interacting physical phenomena they must provide a single framework to accommodate a family of procedures to solve the resulting coupled set of non-linear discretised equations. To be efficient, the family of solution procedures really has to be well integrated; in effect, it has to be a single code and so employ a consistent discretisation procedure. Multiphysics modelling problems generally involve:

- a large number of continuum variables, typically 10-20,
- a complex unstructured mesh (10^5-10^6 + nodes)
- substantial temporal resolution (often 10^3-10^4 time steps)

Given that the coupled sets of equations constituting the multiphysics models are highly nonlinear, the numerical solution is extremely challenging from a computational perspective; as such, these modelling software tools need to be implemented and used on high performance parallel computers.

One effort to produce multiphysics modelling tools has been led by Hughes of Stanford University and CENTRIC Corporation[3]. The software product, SPECTRUM, is based upon a finite element discretisation procedure and facilitates fluid flow, solid mechanics and heat transfer with reasonable measures of coupling.

3. DESIGN AND IMPLEMENTATION OF THE MULTI-PHYSICS MODELLING SOFTWARE TOOLKIT-PHYSICA

Motivated by the need to model a range of processes essentially characterised by solidification phase change (involving free surface turbulent fluid flow, heat transfer, solidification/melting, electromagnetics and solid mechanics), the authors and their colleagues have been involved in the development of techniques and software tools to analyse such closely coupled interacting phenomena for some years. From the earliest days it was apparent that to implement such models would require a novel single software framework[4]. Below we outline the key principles and features of the multi-physics software, PHYSICA, that has resulted from this effort[5,6].

3.1 Finite Volume-Unstructured Mesh Context

The main reason for choosing FV procedures over their FE counterparts was because a) they generally involve segregated iterative solvers for the separate variables which are then coupled (very effective for highly non-linear equations) and b) their natural conservation properties at the cell or element level. Given that it is now well established as straightforward to generate a non-overlapping control volume for any kind of mesh, then it is useful to exploit unstructured meshes for the accurate representation of geometrical features.

Given that the key phenomena of interest can be expressed in a single form:

$$\frac{\partial}{\partial t}\int_{v} \rho A\phi dV = \int_{s} \Gamma_{\phi} \mathrm{grad}\phi \underline{n} ds + \int_{v} Q_{v} dV - \int_{s} Q_{s} \underline{n} ds$$

where Table 1 provides a summary of the main continuum equations describing fluid flow, heat transfer, electromagnetics and solid mechanics, then it should be quite possible to extend established FV methods to all the above phenomena on unstructured meshes.

FV methods on single and multi-block structured meshes are well established for Navier Stokes fluid flow heat transfer[7,8]. Their extension to turbulent compressible flow on unstructured meshes has been achieved without difficulty[9], as have procedures for solidification/melting phase change[10], free surfaces[11] and magnetohydrodynamic[12] systems. Essentially, whatever has been achieved in a structured context can be extended to unstructured meshes. The key gap in the FV context used to be solid mechanics, however, in the last five years a number of groups have worked on FV procedures for most non-linear solid mechanics problem classes[13-19]. They have been extended straight-forwardly to unstructured meshes and are as accurate as their FE equivalents.

At this stage we have demonstrated that there are now a range of FV-UM solution procedures that solve fluid flow, heat transfer, electromagnetics and solid mechanics processes. These procedures provide the basis for the design and implementation of a multi-physics modelling soft-ware tool.

3.2 Design of the multi-physics modelling software framework, PHYSICA

The core of PHYSICA is a three-dimensional code structure which provides an unstructured mesh framework for the solution of any set of coupled partial differential equations up to second order[5,6]. The design concept is as object oriented as possible, within the constraints of FORTRAN77, and the challenge has been to build a multi-level toolkit which enables the modeller to simultaneously:

- focus upon the high level process of model implementation and assessment,
- exert maximum direct control over all aspects of the numerical discretisation and solution procedures.

The object orientation is essentially achieved through the concept of the mesh as constructed of a hierarchy of objects - nodes, edges, faces, volumes which comprise the mesh, see Figure 1. Once the memory manager has been designed as an object hierarchy, then all other aspects of the discret-isation and solution procedures can be related to these objects. This enables the software to be structured in a highly modular fashion, and leads to four levels of abstraction

- **Model** - where the User implements the multi-physics models
- **Control** - which provides a generic equation (for exploitation by the User) and solution control strategies
- **Algorithm** - a whole set of tools for discretisation, interpolation, source construction, managing convection and diffusion, properties, system matrix construction, linear solvers, etc
- **Utility** - file input-output tools for interaction with CAD software, memory manager, database manager, etc.

With the abstraction framework it is quite possible to implement discretisation and solution procedures to analyse distinct continuum phenomena in a consistent, compatible manner that particularly facilitates interactions. The initial version of PHYSICA has a) tetra-hedral, wedge and hexa-hedral cell/element shapes, b) full adaptivity implemented in the data structures which are consistent for refinement/coarsening and c) a range of linear solvers. It has the following core models:

- single phase transient compressible Navier-Stokes flow with a variety of turbulence models
- convection-conduction heat transfer with solidification-phase change and simple reaction kinetics
- elastoviscoplastic solid mechanics

and their interactions. Work is currently at an advanced stage to include free surface flow, contact mechanics and electromagnetics. The PHYSICA toolkit outlined above and its prototypes are currently being used in the modelling of a wide range of manufacturing processes, including shape casting, twin roll casting and soldering.

3.3 Implementation on high performance parallel systems

In the last few years, there has been a convergence on the use of commodity (workstation) processors, grouped into clusters of 4 or 8 sharing memory over a single bus, with the clusters connected together by a high speed communications link to form scaleable high performance parallel computing systems. Typical of this style of parallel system, which is much more affordable than the conventional large scale super-computer, is the SGi Origin 2000 and DEC Alpha 4100 products. These families of hardware will form the high performance compute engines that are required if multi-physics simu-lations are to play a practical role in the virtual manufacturing environ-ment of the future.

Of course, a good deal of work on strategies and tools to facilitate efficient parallelisation of computational mechanics (CM) codes has been done in the last decade. Much of this has been charted by a number of conference series (see, for example, the SIAM Parallel Processing for Scientific Computing[20], Parallel CFD[21] and Domain Decomposition Proceedings series[22]. The predominant paradigm used in the parallelisation of

CM codes, and exploited in PHYSICA, is known as Single Program Multiple Data (SPMD). Here, every processor essentially runs the same program, each one only operates on the data associated with its component of the mesh covering the domain volume. The key tasks to be completed in parallelising such a code are:

- partitioning of the mesh to ensure load balancing and to minimise the number of cells/ nodes at the interfaces between submeshes
- reshape the code to operate on reduced array space
- install masks to ensure functions only operate on processors where data is stored
- introduce synchronisation points and communication calls using one of the standard libraries (eg. PVM, MPI).

In fact, of course, the parallelisation is done generically so that the number of processors and the mesh (and its partition) are specified at run time. The partitioning tool used in the parallelisation of PHYSICA is JOSTLE, developed by Walshaw et al[23,24].

4. ILLUSTRATIVE RESULTS

4.1 Shape Casting of Metals

Although shape casting is as old as civilisation itself, it is still a vitally important process today in the manufacture of high integrity aircraft and automotive components. As stated above the process involves:

- free surface flow as the mould fills
- residual convection, and possibly, electromagnetic fields to control it
- heat transfer and solidification
- the development of internal stresses and deformation as cooling proceeds.

Significant efforts at developing a multi-physics model of the shape casting process have begun to bear fruit in the last year or two[25]. In Figure 2, we show various stages in the filling of a benchmark case sand casting mould[26]. The deformation of the component at the end of solidification is shown in Figure 3 and the cooling performance is shown in Figure 4. One of the key objectives in producing a model with such complexity, is to be able to predict structure integrity based upon phenomenological interactions. The prediction of macroporosity relies on the interaction of all the above phenomena. In Figure 5 we show a simulation example of predictions of internal and surface macroporosity for a metal; the only difference between these cases is that a) has a short and b) has a long solidification temperature range. All other conditions are identical[27]

To give some idea of the compute demands, the 3D benchmark case above required a mesh of 35000 nodes and the problem required ~2500 time steps. Given the substantial number of calculations, it is not surprising to learn that the processor time on a DEC Alpha 433 Mhz system was ~36 hours.

4.2 Solder Joint Formation

As electronic components become ever smaller, then the key joining technology has to meet ever more stringent levels of quality and reliability. Both of these factors depend on the level of precision and control achieved during the soldering process. In this process there are three key phenomena:

- the role of the surface tension forces in determining the primary shape of the liquid solder in the solder-joint complex,
- the cooling heat transfer and solidification,
- the development of residual stress,

with liquid convection forces playing a significant, but secondary role. A three-dimensional model of this process has been developed[28] using the EVOLVER code[29] coupled with PHYSICA. EVOLVER is a surface definition software tool; given the surface properties of the solder, its volume and the geometrical context, this FE based algorithm will predict the shape of the solder volume. PHYSICA is then used to calculate the heat transfer and residual stress development. The ultimate objective is to include the convection flow effects and couple the condition dependent behaviour of the liquid solder into the dynamic development of the solder shape.

Figures 6 and 7 show some results of the model to-date. In Figure 6, we show the geometry of the solder complex. Here the shape assumed by the liquid solder in the complex is determined by the surface tension based energy minimisation equations using the EVOLVER code[29]. Also shown are a typical cooling curve, liquid volume fraction and effective stress development at one location as a function of time. It is interesting to note the rapid rise in the effective stress just below the solidus temperature. The development of the stress is further illustrated in Figure 7 which shows von Mises stress contours at different times; notice how the stress concentration is at the solder-board interface. This is a combination of the thermal gradients generated and the large disparity in the coefficient of expansion of these materials.

4.3 Parallel performance

Parallel PHYSICA has been tested in a number of models and hardware configurations. In Figure 8 we show the results of a relatively modest sized model using 9000 cells/elements and solving for about 10 "transported" variables on a range of systems:

- the CRAY-T3D system at Edinburgh University
- an IBM SP-2 system at Southampton University
- a DEC Alpha 466 Mhz system at Greenwich.

In raw speed-up terms, the DEC and CRAY systems are similar; moreover, the fact that the parallel efficiency is retained up to 64 processors demonstrates the scaleability of the parallelisation strategy on appropriately balanced systems (ie. with a sufficiently low interprocessor communication: processor compute speed ratio). The relatively slow interprocessor communications of the IBM SP system is the reason for its poor speed-up performance. Having said this, because the processor speed of the IBM SP system is somewhat faster than the CRAY-T3D machine, its elapsed times are competitive. However, by far the best parallel performance is delivered by the DEC system. Besides high parallel efficiencies, the elapsed time on a 12 processor DEC system will not be matched on the CRAY-T3D unless 100+ processors are used. These results provide evidence to confirm the earlier assertion of the increasing role of modest scale parallel systems based on commodity workstation processors.

5. CHALLENGES IN THE UTILISATION OF MULTI-PHYSICS MODELLING SOFTWARE TOOLS

It is one thing to have available multi-physics modelling software tools and quite another to make effective use of them. Particularly in relation to manufacturing processes involving solidification phase change, it is not straightforward to configure such software to represent a sufficiently comprehensive model of each process. This complexity arises from the mathematical and physical structure of the model, combined with the problems associated with the adequate specification of a multi-material domain with complex geometries. The latter is a problem because, for manufacturing purposes the geometry is preferably specified by surface modelling. However, this approach does not guarantee the integrity of the shape volume, where solid modelling is preferred. Actually, even with solid models the generation of an adequate quality discretisation mesh is still a considerable challenge. The solid geometry-mesh generation technology is still neither sufficiently comprehensive nor robust!

Although, design engineers have been used to using FE software to analyse the performance of components for many year, there is no real model building - this has already been done and the engineer simply configures an established FE model to perform a specific analysis. With regard to the family of solidification based manufacturing processes the situation is not so advanced. With the exception of some shape casting processes where some models have been developed, most other solidification based manufacturing process models require careful formulation, implementation, testing and validation before they can be used with confidence. The model building process is not straightforward and requires specialised skills, normally beyond the conventional design engineer.

What makes the problem of multi-physics analysis worse, is that aside from deformation and residual strength, the design and manufacturing engineers are not really interested in anything else produced directly by the model. However, they are interested in factors that are a consequence of the multi-physics behaviour of the process - notably the soundness of the product and its material properties. Unfortunately, the mapping of the physical history to the development of material properties is a development in its infancy from the perspective of a phenomenological basis. However, it is the next significant challenge for the modelling community once the frameworks for multi-physics modelling have been robustly established.

With regard to the concurrent engineering process in the virtual manufacturing environment, the facility to model the physical manufacturing operating should provide a clear communication tool for both the design and manufacturing engineers to optimise the component (or assembly) with respect to manufactured properties and operational performance before expensive experimental trials commence.

6. CONCLUSIONS

In the context of the virtual manufacturing environment, the role of computational modelling software tools to facilitate simulation of the component manufacturing process is fundamental. Unfortunately, these software tools have to enable the representation of the interactions between continuum phenomena. To achieve this requires a new generation of modelling software tools that have been designed to facilitate multi-physics, rather than primarily focused upon a single phenomenon (eg. fluid flow, solid mechanics) as is

currently the case. The development of one such multi-physics modelling software tool has been briefly described above, for which a parallel implementation is a basic requirement, given the large compute demands of these models.

Even given effective multi-physics modelling software tools, there is still a demand for

- high quality geometry representation and mesh generation tools

- the ability to map the physical history of the manufacturing process to material properties.

The delivery of adequate computational models at the heart of the virtual manufacturing process remains a considerable challenge. All that we have been able to achieve here is to identify the state-of-the-art and raise some of the key issues that need to be addressed.

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Phenomenon	φ	A	Γ_φ	Q_v	Q_s
Continuity	1	1	1	S_{mass}	$\rho\underline{v}$
Velocity	$\underline{v}$	1	Γ_v	$(S+\underline{J}\times\underline{B}-\nabla p)$	$\rho\underline{v}.\underline{v}$
Heat transfer	h	1	k/c	S_h	$\rho\underline{v}h$
Electromagnetic	$\underline{B}$	1	η	$(\underline{B}\nabla)\underline{v}$	$\underline{u}.\underline{B}$
Solid mechanics	$\underline{u}$	$\partial/\partial t$	μ	$\rho\underline{f}_b$	$\mu(\text{grad }\underline{u})^T+\lambda[\text{div }\underline{u}-(2\mu+3\lambda)\alpha T]\underline{I}$

TABLE The key arguments for the generic partial differential equation characterising continuum phenomena

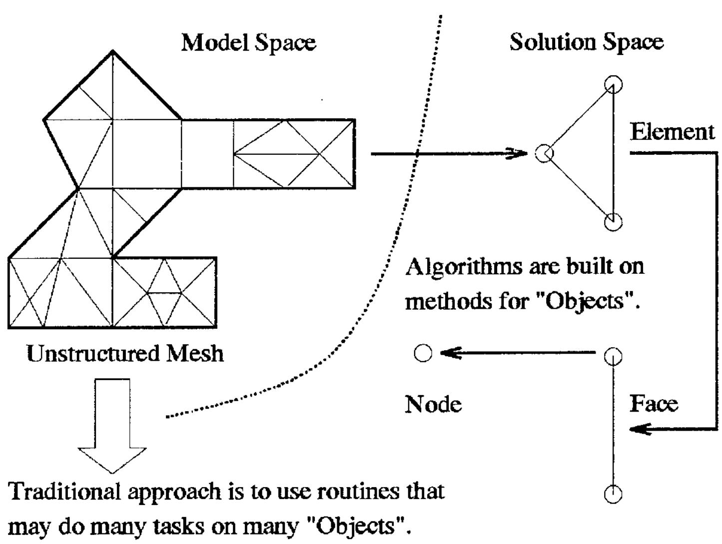


Figure 1 Object based design concept of PHYSICA

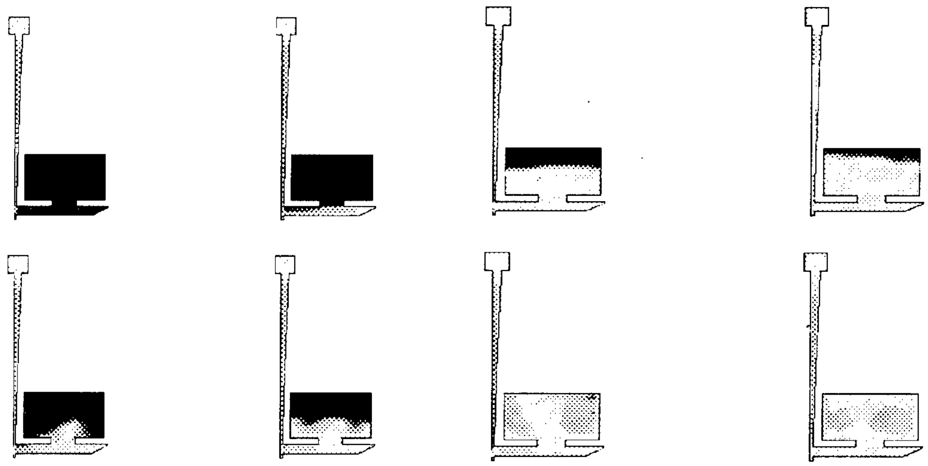


Figure 2 Various stages of the benchmark case for mould filling

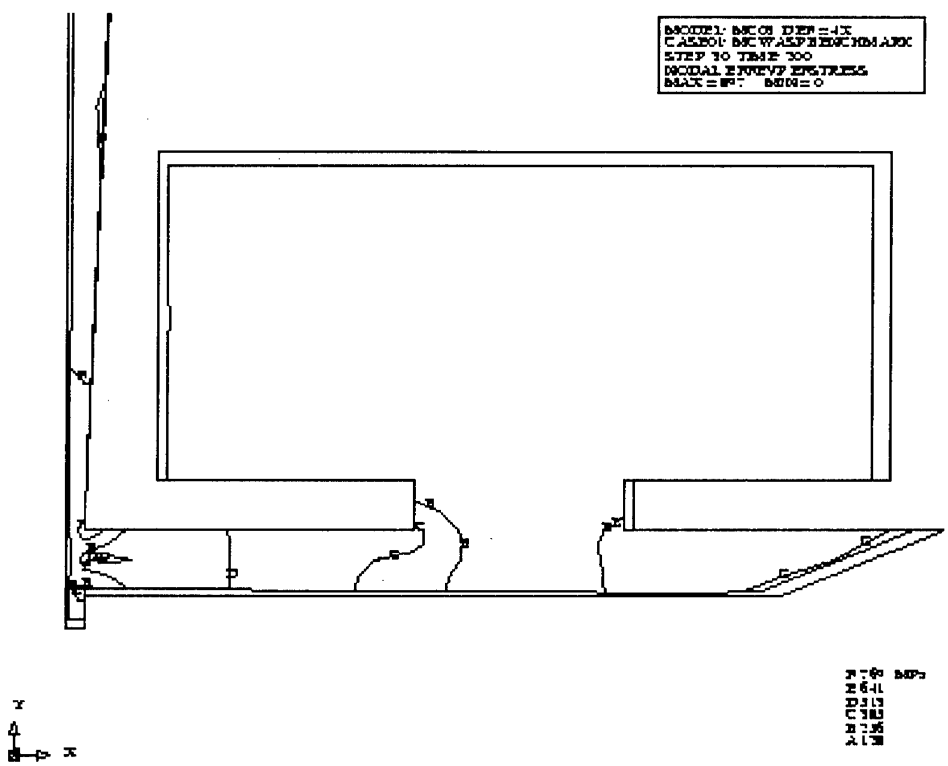


Figure 3 Component deformation and stress development in the benchmark case

Solidification times (secs)

location	expt	model
A	63.7	61.5
B	60.2	61.5
C	18.6	14.0
D	13.2	14.0
E	10.6	11.0
F	15.3	15.0
G	11.9	12.0

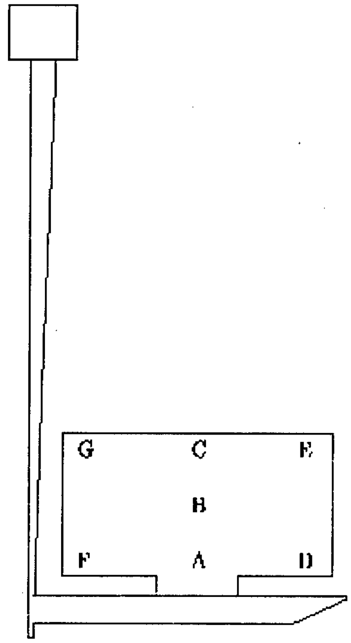


Figure 4 Comparison between measured and predicted solidifications at various locations for the benchmark case

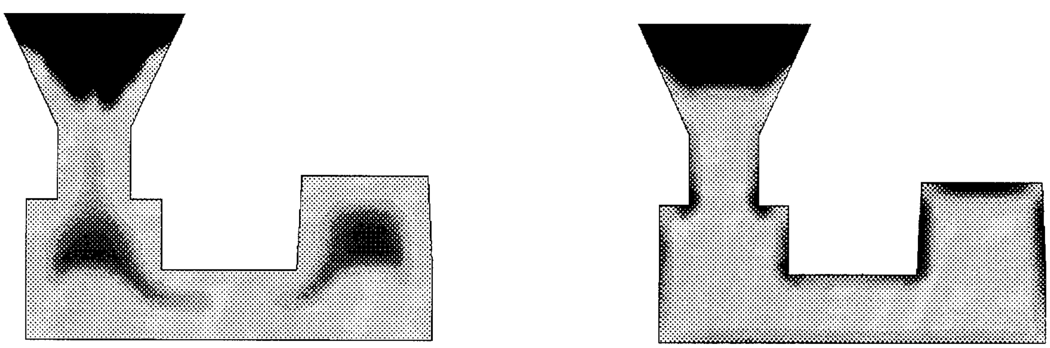


Figure 5 The impact of a) short and b) long solidification range on the macroporosity distribution

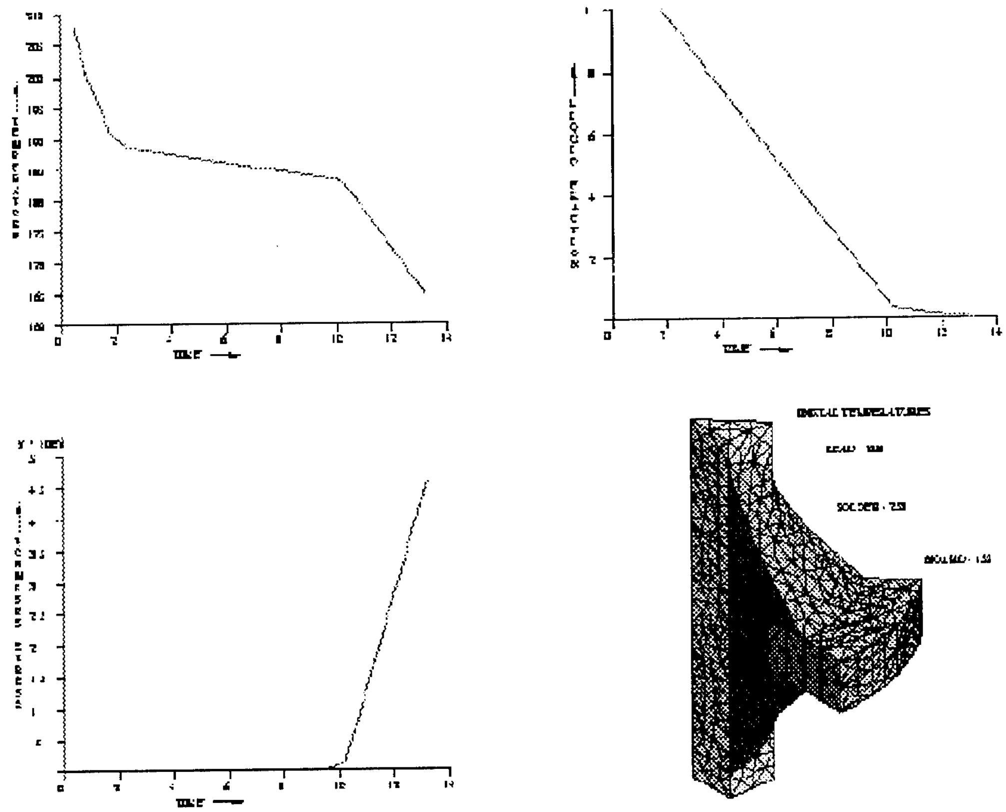


Figure 6 A solder joint geometry and some aspects of the cooler behaviour at one location

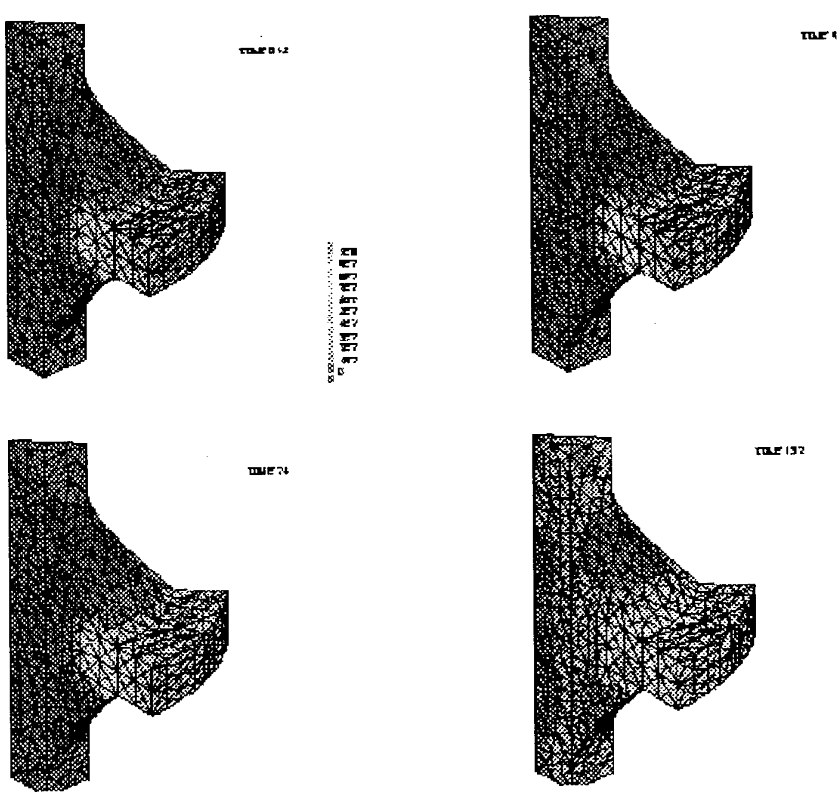
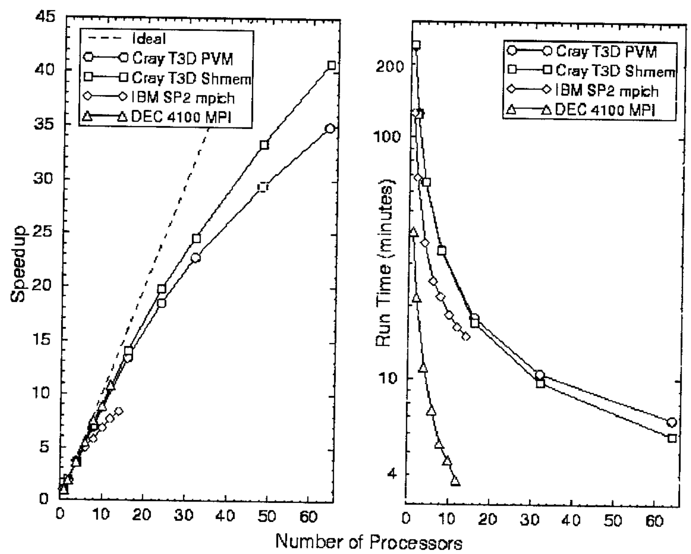


Figure 7 The development of stress at the solder-board interface as cooling proceeds.



(a) (b)

Figure 8 Speed-up and elapsed times on parallel PHYSICA for a multiphysics problem on various forms of HPC hardware

COST ENGINEERING - A FEATURE BASED APPROACH

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SUMMARY

This paper will outline British Aerospace's (BAe's) development of Cost Prediction / Management methodologies and toolsets and their relationship to feature based modelling. It will place these developments within the context of the in-house implementation of Integrated Product Definition (IPD) currently being addressed within BAe Military Aircraft & Aerostructure's (MA&A's) requirements for Business Process Re-engineering (BPR) and Operational Efficiency Improvement (OEI).

An outline of BAe's commitment to the philosophy and implementation of Integrated Product Development is given in **Section 2**.

Section 3 provides a history of Cost Engineering and it's Design To Cost (DTC) toolset developments.

Multi-Disciplinary Optimisation (MDO) as an enabler to efficient Cost Prediction is discussed in **Section 4** together with an example of an MDO toolset currently in use within BAe's Airbus Operations Company at Filton.

Section 5 introduces Feature Based Costing. How 'features' relate to both the design and costing processes is discussed together with an outline of BAe MA&A's development of its 'Cost Prediction and Management system' pilot study.

Conclusions related to the Cost Prediction process and the importance of 'features' are offered in **Section 6**.

Abbreviations

BAe - British Aerospace
BOM - Bill Of Materials
BPR - Business Process Re-engineering
CA - Cost Advantage™
CAD - Computer Aided Design
CAPPS - Computer Aided Process Planning System
CBS - Cost Breakdown Structure
CEDAMS - Cost Engineering Database And Management System
CER - Cost Estimating Relationship
DFM - Design For Manufacture
DOC - Direct Operating Cost
DPA - Digital Product Assembly
DTC - Design To Cost
FBCA - Feature Based Cost Algorithms
IBLS - Integrated Business Logistic System
IE - Industrial Engineering
IPD - Integrated Product Development
IPT - Integrated Product Team
KBS - Knowledge Based System
MA&A - Military Aircraft & Aerostructures
MDO - Multi-Disciplinary Optimisation
MMS - Materials Management System
NRC_e - Non Recurring Cost for Engineering
NRC_m - Non Recurring Cost for Manufacturing
OEI - Operational Efficiency Improvements
PDM - Product Data Manager
RC_m - Recurring Cost for Manufacture
SPF/DB - Superplastically Formed and Diffusion Bonded
TADPOLE - Transport Aircraft Design Program with Optimisation Logic Executive
WAPCO - Whole Aircraft Parametric Cost Optimiser

1.0 INTRODUCTION

As a result of changes in the Military Aircraft marketplace, the emphasis on Cost has changed from being purely a commercial consideration to being a major parameter in the design / manufacturing process.

This necessitates the Integrated Product Team's (IPT's) being equipped with a system that can predict

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manufacturing costs, from product design information, quickly and without the need for specialist knowledge. The system must be integrated into the Digital Product Assembly (DPA) architecture and be useable throughout all stages of the design / manufacturing process.

Such a system would facilitate product and process cost reductions consistent with the objectives of OEI / BPR, by empowering the IPT's to perform detailed cost trade studies. It would bring about optimised designs by adopting low cost manufacturing techniques and would provide an increase in cost awareness.

The primary enabler to this requirement, the Integrated Product Development process, together with its subset Digital Product Assembly, is detailed below.

2.0 INTEGRATED PRODUCT DEVELOPMENT

Integrated Product Development (IPD) was established at BAe Military Aircraft & Aerostructures (MA&A) as a result of the findings from the in-house 'Operational Efficiency Improvement' (OEI) group. The overall objectives set by the OEI group focused on improving existing activities and meeting the following goals by the year 2000 :-

- Reduce process costs by 30%,
- Reduce process elapsed time by 50%,
- Achieve 100% adherence to schedule, quality and cost,
- Establish seamless, concurrent processes across Operations.

Essentially; the organisation recognised that, to remain competitive in the market place, it must change from its existing serial based product definition environment to a 'concurrent', seamless organisation.

This desired change is depicted in Figure 1 and highlights the importance of the 'Integrated Product Development' process.

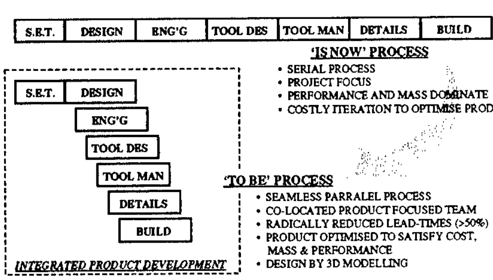

Figure 1

IPD is defined as a combination of the four principal topics outlined below :-

1. Organisation
   Based on empowered Integrated Product Teams (IPT's) supported by a consolidated Operations organisation.

2. People
   With the required skills, knowledge, and culture to work in the new organisation.

3. Information Technology
   To support the process in configuration management, data creation / sharing, storage, product modelling and analysis.

4. Process
   Providing a structured and phased approach to product development which can be applied right across the product lifecycle, from concept to decommission.

In essence, IPD provides a basic framework to apply maturity / risk gates, with clear input and output criteria, to aid decision making. It allows the control of product development to be approached in a similar, generic way for all projects.

A schematic of the IPD process is shown in Figure 2.

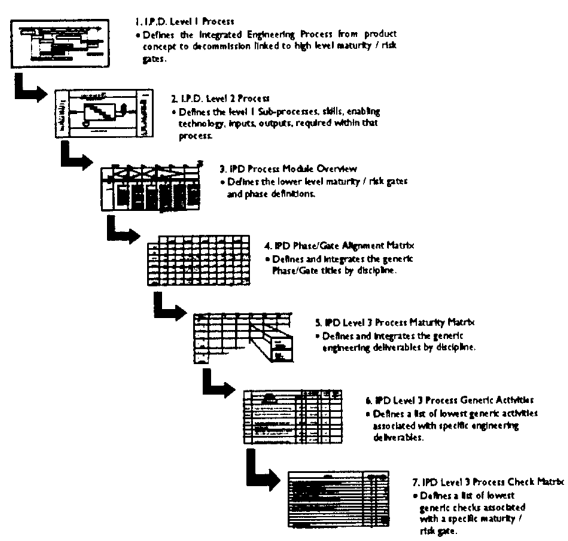

Figure 2

As an element of IPD, Digital Product Assembly (DPA) provides the organisation with the appropriate toolsets necessary to discharge the product development

activities in line with the four topic areas previously discussed.

DPA is a key project within the IPD framework of projects. Its objectives are structured around the business requirements supporting the OEI goals and are as follows :-

- Developing MA&A's capability to create and complete accurate three dimensional digital representations of Aircraft Structures and Systems.
- Implementing that capability with it's associated technologies, tools and processes to support BAe's products from concept to disposal.
- Integration and automation of related engineering processes.
- To simulate both product Performance and Manufacturing Process.

In addition to providing many benefits in its own right, DPA is a key enabler for concurrent engineering, seamless processes and cycle time reduction throughout the MA&A product life cycle.

DPA is being introduced into the company using a phased approach. The applications of DPA are not merely concentrated on one particular aircraft project; the process, when adequately mature, will be used as a key part in the design, development and manufacture of all aircraft projects across the BAe spectrum.

The DPA vision is outlined below (Figure 3) which shows the ongoing developments in Computer Aided Design (CAD), data exchange and the interface with the factory and enterprise systems.

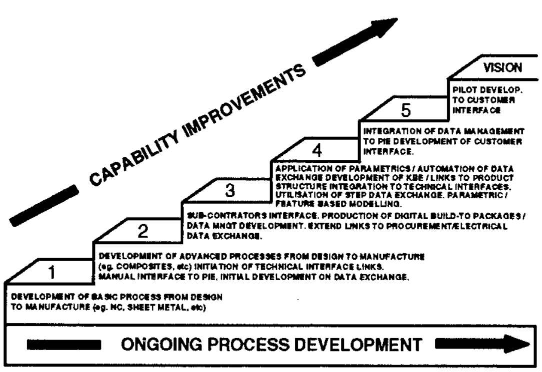

Figure 3

Within the design / manufacturing areas; the introduction of the seamless environment as envisioned in IPD, coupled with the advances in DPA, have identified the need for a radical change in the Cost Prediction process. This requirement is also evident in the commercial and production support areas as a result of their initiatives in BPR.

The following section will give a brief history of the Cost Engineering group at MA&A's Warton site and will outline the developments of Design To Cost (DTC) systems employed at that site.

3.0 COST ENGINEERING HISTORY

In common with most aerospace companies in the '70's, BAe maintained a Value Engineering group and engaged them in post-design cost reduction activities. The techniques used were typical of the time and followed the principles of optimising the manufacturing processes related to the existing design. The group consisted of experienced engineers fully conversant with the state of the art manufacturing techniques employed at the various production sites. These engineers identified the high cost design solutions, offered alternatives and followed the changes through the production easement process. There were virtually no cost targets in this approach - the only goal being the reduction of cost based on the datum aircraft as defined by the design office.

This requirement followed the prevailing economic climate and reflected the acquisition policies of the customer - namely 'cost plus' contracting.

The significant change from the 'cost plus' environment to 'fixed price' contracting signalled the end of the traditional, post design, Value Engineering based cost reduction approach, and forged the new age of 'Design To Cost'.

The Cost Engineering group was subsequently formed and began the development of BAe Military Aircraft Division's (now an element of MA&A) knowledge based, DTC systems.

The first custom made DTC system was conceived during the early 1980's and was instigated as a requirement of the Eurofighter 2000 (then EFA) program.

Two further generations of system have been developed; each expanding the cost prediction capability with the latter also introducing the concept of a centralised Cost Management facility.

The three existing systems are briefly described in the following text :-

3.1 'Savoir' - First generation system

The first Design To Cost system developed at Warton was the 'Savoir DTC System' and was conceived in the early 1980's.

This system was developed using the SAVOIR application and was resident on an IBM mainframe.

The algorithms embedded in the system were based largely on Tornado production components and were built in such a manner that each individual 'cost significant' process step was encoded as a separate element. This approach was adopted such that any improvement in process, usually relevant to one or more steps, could easily be incorporated in updates to the algorithms.

The initial customer of the system was the Cost Engineering group however, as its capability became more robust, it was incorporated as a Design procedure and became an element of the design release process.

Training of all design personnel was carried out and the system was used throughout the concept phase of the Eurofighter (then EFA) project.

The Savoir DTC system provided the Cost Prediction element of the 'Cost Management Process' developed for the EFA project. This process consisted of the following steps :-

1. Cost targets were allocated to pre-determined product 'zones' (assemblies or components),
2. Cost was predicted using the DTC system for several potential design solutions,
3. The optimum solution was selected and it's cost monitored and tracked as more detail was developed,
4. Cost was then aggregated to provide the total cost for the airframe section (ie. wing, front fuselage etc.).

3.2 'Leonardo' - Second Generation system

In the early 1990's, development of the second generation DTC system - 'Leonardo' - was initiated. In this instance, it was a Knowledge Based application and was VAX based.

The algorithms for the Leonardo system were classed as 'pseudo synthetics'. They were derived either directly from Industrial Engineering (IE) synthetics where the equations could be related to each operation or, indirectly, whereby the relationship of parameters were derived from the aggregation or average of several IE standards.

3.3 'CEDAMS' - Third Generation system

CEDAMS, the 'Cost Engineering Database And Management System' was a mainframe based development of the two preceding systems. Development began in 1993 and the system was built around a DB2 database and was programmed using the 'Natural' language.

The philosophy behind CEDAMS was such that the Cost Prediction capability could be integrated with a database facility to enable all cost and product data to be stored in a consistent manner.

Subsequently, data could be retrieved, adjusted and re-entered such that 'like part' costing could be accomplished during the concept phase. The data could also be used to develop updated CER's as product and process data was generated.

CEDAMS was also capable of holding 'part relationships' (ie. part / sub-assembly / major assembly) and had the facility for automatic aggregation of cost for Cost Management purposes.

The Cost Engineering group at BAe MA&A's Warton site are currently developing a 'fourth generation' Design To Cost (DTC) system. This system will exhibit both Cost Prediction and Cost Management capabilities and is being created around the use of product features. Further details of this system are given in Section 5.0.

4.0 MULTI-DISCIPLINARY OPTIMISATION

An enabler to the efficient use of a feature based approach to 'costing' is the multi-disciplinary approach to product definition.

In general, a lack of commonality exists both across disciplines and across directorates when considering 'cost'. This is understandable when, during the creation of a machined frame for example, the designer views the peripheral flange as being an additional feature of the part whereas the manufacturing engineer views it as a feature created as a result of removing material.

These contrasting viewpoints become further complicated when the commercial, customer support and procurement disciplines offer their perspectives. As a consequence, a common language and a consistent approach to trade study analyses are required. This commonality can, to a large extent, be provided by the use of features (as the common language) in a Multi-Disciplinary Optimisation (MDO) environment for the trade study process.

One example of a multi-disciplinary approach, using features, for structural, performance, customer satisfaction and cost optimisation is used at the BAe Airbus Operations site at Filton.

This system, called 'TADPOLE', is briefly described below.

4.1 'TADPOLE' - Multi-disciplinary Optimisation routine

BAe's Airbus Operations Company, based at Filton, are responsible for the design and manufacture of wings for the Airbus family of aircraft.

In concert with the current emphasis on product affordability, Airbus Industries are asking for their products to be designed to be more cost effective to manufacture and to be more cost effective for their customers to own.

Traditionally, most aircraft designs were fully optimised for aerodynamic efficiency at minimum weight - with manufacturer's and operator's cost historically being considered as a secondary requirement. A toolset was required which was capable of assessing all these parameters during the optimisation process.

The Future Projects Office at BAe's site at Filton utilise an optimisation tool called TADPOLE (Transport Aircraft Design Program with Optimisation Logic Executive) which performs such an activity and is shown diagrammatically in Figure 4 below.

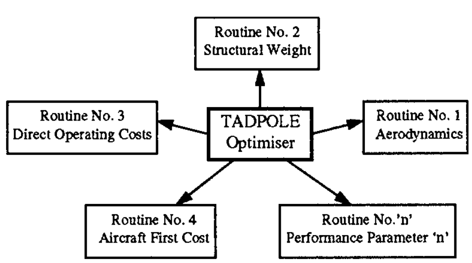

Figure 4

The tool consists of an array of FORTRAN routines which orbit a mathematical optimiser. To perform the optimisation of the required product, the engineer creates a number of data sets that represent the proposed aircraft. This includes such things as engine number, engine position, fuselage diameter, length, flight profiles etc. Once this data is in place, TADPOLE optimises the proposed aircraft's configuration for aerodynamic suitability, structural weight, DOC (direct operating cost) etc. TADPOLE may consider over 10,000 different configurations before delivering what it believes to be the 'optimised' aircraft.

When TADPOLE was conceived, manufacturing cost was recognised to be one of the optimising parameters for the aircraft. A TADPOLE routine named 'First Cost' attempts to calculate the development and manufacturing costs of the proposed aircraft. The routine then goes on to predict the selling price of the product.

Unfortunately, the costing routine which calculated the development and manufacturing costs of the proposed aircraft was not being employed. This was largely due to the data set required by the routine being incomplete, out of date and not really understood by the user.

Recent developments (circa 1996) carried out by the Filton based Cost Engineering group re-instated the 'First Cost' routine as an optimising parameter and significantly expanded the capability of the TADPOLE optimisation tool by enabling a feature based product structure to be built as an element of the iteration process.

The revised toolset is illustrated in Figure 5 and shows the addition of WAPCO (Whole Aircraft Parametric Cost Optimiser) which provides the TADPOLE optimisation system with a much improved cost optimisation capability and introduces 'features' into the iteration process.

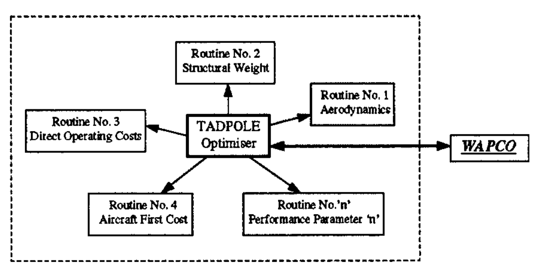

Figure 5

WAPCO harnesses the strategies and rules of thumb that are an essential part of the conceptual design process. In BAe Filton's case, examples of these strategies are :-

- interspar ribs pitched at approx. 750mm
- stringers pitched at approx. 160mm
- 2 rows of fasteners typically attach spars to skins
- manholes are present in interspar ribs when depth exceeds 700mm.

Manufacturing constraints are also taken into account in the WAPCO routine such as the limitations in

machine tool bed size, and the limits of material billet size which drive the introduction of wing skin joints.

WAPCO utilises the previously mentioned strategies and rules of thumb and develops the full product structure of the aircraft ready for cost assessment. An extract showing a partial product structure for a wingbox is shown below as Figure 6.

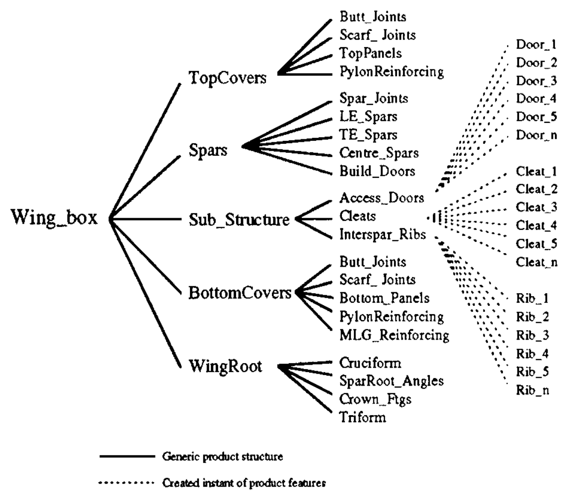

Figure 6

'Instances' of the generic product structure, indicated by the dotted lines on Figure 6, are created by WAPCO receiving basic geometry from TADPOLE and employing the design strategies mentioned earlier to determine the quantity of cleats, access doors etc. These created 'instances' will include the features or attributes required by the embedded Feature Based Cost Algorithms (FBCA).

The use of features in WAPCO flows through the routines from the generation of the aircraft product structure outlined above [commonly known as the Bill Of Materials (BOM)] through to a lower level of modelling where each object or product element is considered and its attributes or component features are determined.

Using these features, Cost Breakdown Structure (CBS) elements, such as RC_m, NRC_e and NRC_m can be derived using the FBCA's.

Updates to the Optimisation system are constantly being developed. From a costing viewpoint, predictions using advanced materials and processes are providing the largest challenge.

In this instance, revised product structures are being developed together with FBCA's which, through features, will recognise these advanced technologies and ultimately be able to provide comparisons, during the conceptual phases of the project, with current, 'state of the art' technologies.

5.0 FEATURE BASED COSTING

With the advent of significantly different structural forms accompanied by radically different materials, such as blended body airframes manufactured using advanced composites and SPF/BD titanium, the traditional, historically derived parametric models become unusable without intuitive, experience based factors being applied.

Features, in these instances, can be a vital element in the cost prediction process particularly during the early phases of design. This is invariably due to the lack of geometrical definition - the usual data type conventional cost prediction techniques employ.

5.1 Why features ?

The current generation of CAD systems operate using low level geometric entities such as lines, points, curves etc., against which it is almost impossible to assign any engineering intent.

The newer versions of CAD systems are tending toward using 'features' as the vehicle for the definition and storage of product information throughout the hierarchy of the product architecture.

This feature based approach to product definition allows engineering intent to be encapsulated within the feature. This engineering intent is additional to the base geometrical definition and can be in several forms e.g. product function, performance, manufacturing process, behaviour etc.

Features thus provide three vital functions :-

1. a vehicle for describing engineering intent
2. the method for identifying relationships
3. a framework for describing engineering components in engineering terminology

In the absence of a recognised standard, the Warton based Cost Engineering group have defined a series of feature categories to fulfil their requirements. An extract from that database is shown in the table of Figure 7.

This hierarchy of feature types is the approach Cost Engineering at Warton are adopting for their 'fourth generation' DTC system which is currently under development in conjunction with the DPA development of CATIA, its associated Product Data Manager (PDM)

and with the company development of the Integrated Business Logistic System (IBLS) which is the enterprise repository of data.

Feature type	Examples
1. Geometric	Length, Width, Depth, Perimeter, Volume, Area, etc.
2. Attribute	Tolerance, Finish, Density, Mass, Material composition, etc.
3. Physical	Hole, Pocket, Skin, Core, PC Board, Cable, Spar, Wing, etc.
4. Process	Drill, Lay, Weld, Machine, Form, Chemi-mill, SPF, etc.
5. Assembly	Interconnect, Insert, Align, Engage, Attach, etc.
6. Activity	Design Eng'g, Structural Analysis, Quality Assurance, Planning, etc.

Figure 7

5.2 Pilot Study - Cost Advantage™

The Cost Engineering group at Warton are currently evaluating the Cost Advantage™ tool as a means to fulfil MA&A's requirement for a 'fourth generation' Design To Cost toolset.

Cost Advantage™ is a Design for Manufacture (DFM) expert system that provides immediate cost data, design guidance and producibility analysis.

It captures Design and Manufacturing knowledge in the form of cost and producibility algorithms that evaluate a design based on features, materials and manufacturing processes.

The system can be either keyboard driven or can accept part geometry directly from feature based solid modellers, in BAe MA&A's case - CATIA. The use of this Cost Prediction capability enables accurate and immediate feedback to the engineer whilst geometry construction is underway.

Analysis against the embedded Design and Manufacturing rules provide guidance to the engineer that ensures identification of the high cost drivers as they are introduced and carried through the products life cycle. Dialogue with these rules will provide alternatives that can reduce costs and increase manufacturability.

Outputs from this Cost Modelling toolset can be used as direct inputs to other simulation packages.

A diagrammatic view of the interaction between different feature types, currently being built into the Cost Advantage™ application, is shown in Figure 8.

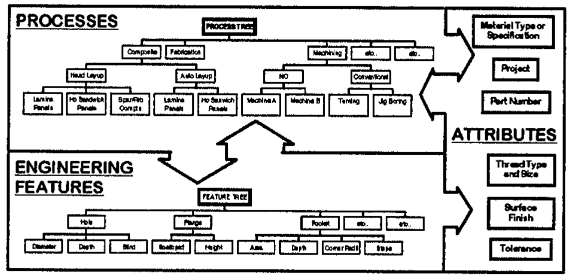

Figure 8

This feature base is an important enabler for the definition of :-

1. the rationalisation of cost across the varied disciplines within the enterprise

2. the cost prediction toolsets necessary for support of product development from the concept phase through to the detail definition phase.

The first issue is process orientated and is being assessed under the IPD framework. This is a 'system independent' problem and the generic requirements for such an environment are being currently addressed. This is discussed in Section 5.2.1.

The second issue is driving the development and implementation requirements of Cost Advantage™. The aim is to provide a coherent set of Cost Estimating Relationships, based on auditable 'bottom level' data which are consistent throughout the product development cycle. Section 5.2.2 outlines this activity.

5.2.1 Rationalisation of 'Enterprise Cost'

Cost is viewed differently by each area of the enterprise and as a consequence each area has developed cost modelling / prediction tools that satisfy its own requirement. This invariably leads to a lack of consistency of data and models.

By using a consistent feature based approach, centred around the product and its feature base, a rationalisation of modelling capability can take place. BAe MA&A are pursuing this goal and are undertaking an exercise to identify the wide variety of models and databases within the organisation. An example of the different types of model, used at different phases in the product development process, by the different disciplines is shown in Figure 9.

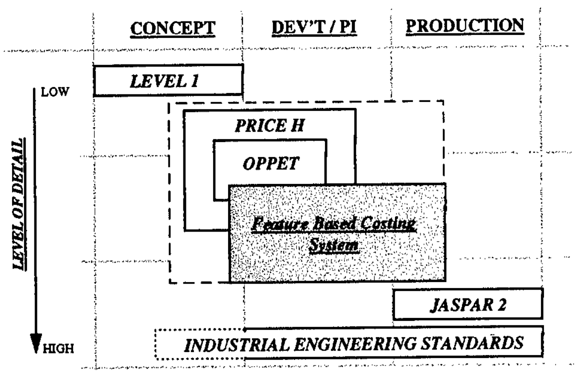

Figure 9

This inconsistency in toolset usage is driving the development of a common toolset which uses Cost Estimating Relationships (CER's), whether they be algorithmically or parametrically based, derived from a 'bottom up' standard of data generated from Industrial Engineering standards. This approach is depicted in Figure 10.

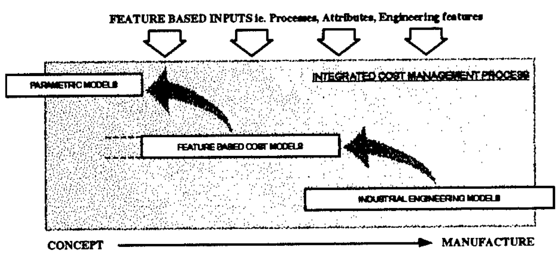

Figure 10

Cost Advantage™ appears to have the functionality to encompass several of the models currently identified and could thus provide a toolset which is capable of providing a coherent approach, across disciplines, for a common Cost Prediction process.

5.2.2 Product development from 'Concept' to 'Detail Definition'

As mentioned earlier, Cost Advantage™ is being developed as the host system for holding the Cost Estimating relationships used during the product development process.

Currently, the CER's previously developed for the CEDAMS system (see Section 3.3), are being re-written to suit the Cost Advantage™ architecture. These CER's are algorithm based and simulate the following manufacturing processes :-

Machining	-	Small Parts, Large Parts, High Speed, Turning
Sheet Metal	-	Flat & Form, Stretch, SPF, Drawn / Extruded
Assembly	-	Minor, Major, Final, Welded, Bonded, SPF/DB
Composites	-	Hand lay, Machine lay, Honeycomb manufacture
Pipes	-	Small bore, Large bore, Lagging
Semi-finished	-	Castings, Forgings

The algorithms are based on Industrial Engineering standards and are related to engineering features and manufacturing processes. They react to data generated in the CATIA sessions (ie. geometry, holes, flanges etc.) and attribute data called into the sessions from the surrounding databases - such as material type and specification, fastener type and specification etc.

Commercial data contained within the Integrated Business Logistic System (IBLS), such as labour rates material cost, fastener cost etc., is applied to the product data and a resultant '£ Sterling' cost is produced. A typical algorithm structure is shown in Figure 11.

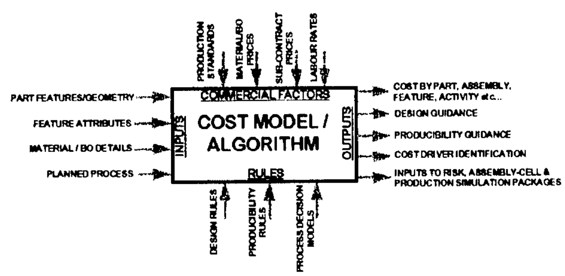

Figure 11

Design rules and producibility rules, which are embedded in Cost Advantage™ are called upon automatically during the Cost Prediction session and, if the product has violated these rules, will advise the engineer 'what' and 'where' the violation is together with and explanation of 'why' it exists.

It is recognised that an essential element of any Cost Prediction process is the need for an integrated database.

Hence, as part of the Cost Advantage™ pilot study and as an element of the drive toward a common Enterprise wide cost prediction toolset, the Cost Engineering group are developing an architecture to underpin the common toolset with a relational database. The

database will capture Predicted and Measured (ie. Production standards) cost data from the toolsets together with it's associated Product, Material, Process and Feature definition.

This will formalise the Cost Management / DTC process thereby allowing consistent monitoring of cost targets and achievement throughout the product development lifecycle.

Furthermore, the database will allow extensive data analysis to support, for example :-

- continuous development of Cost Estimating Relationships (CER's)
- calibration of existing and new cost models
- identification of structure and process cost drivers

Finally, the database will be used to create, or capture, data from surrounding databases to produce look-up tables in support of the cost prediction algorithms. These look-up tables would typically contain information such as material cost, fastener cost, process rates etc.

6.0 CONCLUSIONS

Cost is one of the most important independent variables in today's' product development process. There is a critical need to understand the ability of a product to meet affordability criteria from conception through to manufacture. Traditional practices are not adequate to meet this requirement.

In today's concurrent engineering environment, considerably more information than the traditional geometrical data is needed to support the engineer during the various stages of the design process. The use of a feature based approach would appear to provide the necessary capability to capture and manage the design intent.

The use of features during the product optimisation process has been utilised at BAe's Airbus Operations facility for several years. Improvements to the Cost Prediction routines within the TADPOLE optimisation toolset are as a direct result of the use of a feature based approach. Feature analysis allows the engineer to understand cost without being specifically trained as a Cost Engineer, accountant or production engineer.

Traditionally, cost has been evaluated by utilising 'islands of expertise' spread throughout the enterprise. These islands have independently developed their own toolsets and disconnects in the Cost Prediction process have been evident. A need to rationalise the toolsets and processes has been identified. This approach could offer significant benefits in affordability when coupled with the adoption of Integrated Product Definition together with the capture and storage of consistent data available to all areas of the enterprise.

It is this rationalisation of Cost Prediction Methods and Processes that could, as a result of adopting a feature based approach, become a major enabler in the development of affordable products - a key factor in today's highly competitive marketplace.

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A RADICAL NEW WAY OF PRODUCT DEVELOPMENT - EXPLORING THE BENEFITS WITH VIRTUAL REALITY IN VIRTUAL CONCEPT.

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Abstract

With the introduction of powerful Virtual Reality tools, changes to the product development process have started. However, the potential of these tools are today not fully explored since the changes to the process still is very limited. The technique behind VR and the possibilities that it offers is very promising. Due to increasing performance of computers, at a reasonable low price, it is now possible to implement and use VR for several new tasks that earlier were restricted due to the complexity of the system and cost of the solution. Using it in new areas also put additional requirements on the solutions such as the need for simpler user interfaces. In this paper a new way of using VR technology in product development is described together with some of the benefits it gives. Some of the requirements on the environment is also discussed and a new phrase "Virtual Concept" is introduced as well as a short description on the thoughts behind the model.

1. Introduction

In most articles and papers concerning product development, it is claimed that the Product Life Cycle (PLC) is constantly shrinking, despite the fact that the end products are usually becoming more and more complex.

At the same time as companies are striving to get more volume for each product to get a larger volume to carry the development cost, customers want end product that are tailored for them (the global-local paradox, ref. [3]).

In recent years many of the traditional manufacturing companies that used to have "protected" markets, are facing global competition due to over-capacity in production for many products. Many customers preferred to purchase local gods (US used to have this protection, "an American buys American products"), but this is not true any longer. Competition is now based on a number of criteria's such as cost of the product, quality, time-to-market, environmental conditions etc.

Many successful manufacturing companies are also outsourcing more of the design and production, why an increasing portion of the end value, is created by suppliers and partners.

Paper presented at the AGARD SMP Meeting on "Virtual Manufacturing", held in Aalborg, Denmark, 13-14 October 1997, and published in R-821.

There is a big difference in how far this have gone in different companies. As an example of this we compare an American- with a Japanese auto-manufacturer (see figure 1).

	# OF CARS	# OF EMPLOYEES	# OF SUPPLIERS	IN HOUSE ADDED VALUE
GM	8 Million	850.000	1.650	70%
Toyota	4 Million	37.000	223	27%

Source: PA Consulting Group, 1991

***Figure 1**, comparative data on outsourcing at Toyota and GM.*

The pressure from new manufacturing countries with lower labour cost forces western companies to concentrate on complex (often high-tech) products or to automate production.

The drawback with this is that mass production almost always creates less flexible and more rigid companies. Quality has also traditionally been a competitive weapon used by the western industries. Today quality has expanded from a simple definition or durability to include many more aspects of the offered solution. In the book, Competing on the Eight Dimensions of Quality [2], D Gavin describes quality as a combination of;

1. Performance: The products primary operating characteristics
2. Features: Supplementary characteristics of a product
3. Reliability: The probability of a product failing over time
4. Conformance: Meets established specifications
5. Durability: Measure of product life (to replacement)
6. Serviceability: Ease of repair (downtime, meantime to repair)
7. Aesthetics: The look, feel, sound, and so forth, of a product
8. Perceived quality: Subjective reputation of a product, which includes aspects such as ease of use and product integrity

However, automation, lean manufacturing and quality is also becoming the norm in other parts of the world why time to market to create a "window of opportunity" is one of the major remaining competitive differences. The impact on the end profit that is caused by overrun of time in projects within product development is shown in figure 2.

	ENGINEERING COST	TIME	PROFIT LOSS
HP Project 1	+50%	on schedule	4%
HP Project 2	on budget	+ 6 months	32%
RR Project 1	+50%	on schedule	5-15%
RR Project 2	on budget	+ 6 months	50-90%

Source: PA Consulting Group, 1991

***Figure 2**, numbers from different project at Hewlett Packard and Rolls-Royce Aerospace, 1992, showing the end result on the profit in project with either time or engineering-cost overrun compared with budget and time-plan.*

Successful product development is to create a product people want to buy, when they want it, for a price they are willing to pay and for a cost that provides a good profit margin to the company producing it.

For radical and/or revolutionary products/innovations, there is usually no price-pressure due to the lack of competition, however as time goes and competition catch up the price goes down.

Unless a company can compensate for this by tuning the production or get large-scale advantages the margin goes down as well.

This puts a lot of pressure on companies to make dramatic changes in their way of working. Today it is not possible to get enough benefits from changing tools any more, it becomes obvious for more and more companies that it is time to change the way they are working and to use new tools that gives the benefit they need. Manufacturing companies recognise that these changes can only take place using simulation and using tools to virtually describe the product. Today's CAD/CAM systems are trying to resolve some of these issues but there are some important limitations in today's CAD system why we in this paper will investigate some of the benefits with VR and examine if VR tools are much better equipped for this task.

The book *Virtual Corporation* [1] describes a virtual product
"...mostly exists even before it is produced. Its concept, design and manufacture are stored in the minds of co-operating teams, in computers, and in flexible production lines"

2. The problem

Several of the existing CAD/CAM vendors have since long tried to broaden the usage of their tools to start earlier in the development cycle and also to be used in later phases. The aim has been to shorten the development time by integration of more and more functionality within one package to avoid the problem of converting information in-between different CAD packages and necessary external tools.

One of the major drawbacks from this attempt has been the development of increasingly complex, difficult to use and performance demanding software that today more or less require a full time expert to operate.

Many CAD vendors have taken several steps to accomplish to use CAD in an earlier stage:
- integration of, or interfaces to, styling packages
- integration of low-end kinematics packages
- attempt to simplify the user interface
- creation of sketch-like tools that could be carried forward into 3D CAD design

Steps have also been taken to extend CAD into later phases:

- the addition and integration of CAM tools into the CAD package (to simplify the making of physical prototypes)
- possibilities for rapid prototyping directly from CAD (3D solid) geometry (to build simple physical prototypes without cumbersome CAM work)
- virtual packaging and interference detection (to simulate packaging of virtual components)
- integration of FEM (to simulate structural behaviour)
- integration of kinematics packages (to simulate movement and mechanisms)

One of the main disadvantages with CAD is the lack of a conceptual tool to make it easy for the users, in the very early stages, to develop very simple models (Functional Modelling ref. [2]) for initial concept development.

Some other disadvantages in this area with traditional CAD tools are:

- a concept developer must be able to use several tools but today's CAD tools are to cumbersome to use for a concept developer (bad user interface)
- the tools are built with exact dimensioning in mind witch constrains the more artistic concept designer
- the tools are focused on finishing parts with all details (studies shows that after 20% of the design time an engineer have designed 80% of the details within a model For concept purposes a functional model with approximate dimensions only need 10% of the details)
- due to ease-of-use problems, only CAD designers can use the tools and by this they are reluctant to release any information until they are done with all details
- most CAD systems can only work in an assembly with their own information but in an initial concept stage, one must be able to work with information from different sources.
- most CAD systems can not manage large assemblies (i.e. over thousands of components) due to the architecture and the lack of simplification of the models
- most CAD systems are component centric compared with the assembly centricity of VR tools

If a change is needed after the functional modelling and the Virtual Concept study, all work with the model that has been done, after the initial approximately 10%, that is needed for Functional Modelling (ref. [2]), is a waste of time and money.

With the ever-increasing pressure on shrinking development time and shortening time-to-market, this is unacceptable.

3. Today's solution using VR

With the possibilities of VR, the development process manufacturing companies have the potential of shortening the time-to-market considerably as is shown in figure 3.

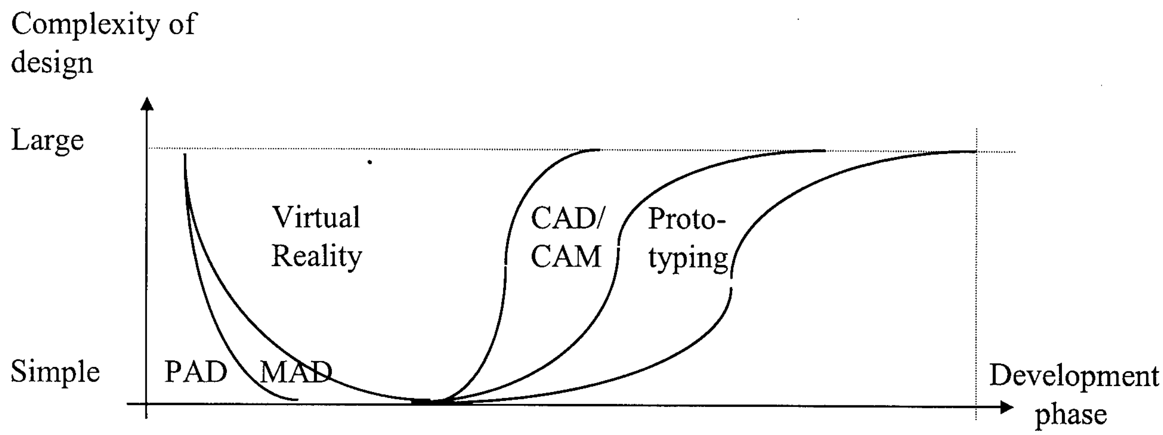

***Figure 3**, tools in different phases of product development (from the paper, Virtual Reality and Product Development, by Stig Ottosson, ref. [1]).*

Note: PAD means Pencil Aided Design, i.e. traditional sketches on paper
MAD means Model Aided Design and refers to the creation of simple physical models i.e. models made by hand of wood, steelwire etc. Things you usually have at home

With the addition of strong Virtual Reality tools, the simulation of components, assemblies and behaviours, have been dramatically improved but they all rely, today, on geometry that has already been defined as a CAD model. The information has then been transferred, and converted, into a suitable graphic format that gives both performance and the flexibility of being CAD neutral.

4. Functional Modelling and Virtual Concept Modelling

Functional Modelling (FM) refers to the limited modelling of any component where the only dimensioning and details that influence the function of the component will be described. A typical example is a link with no details, no fillets etc. but only the extend, and control-points, described. Often only the outline of the object is needed, i.e. for packaging studies, why details are not only unnecessary but also negative due to performance. There are no sharp rules for this but generally, the details that one design in less than 10% of the time for a fully detailed component, is sufficient. The model is as a functional model intended only used for initial studies, packaging, kinematics etc. Only at a later stage when the components have passed functional tests etc. is there a reason to develop them further.

This is traditionally a problem, since the CAD designer, very often do not release any geometry, until he/she has finished the part. Translation of geometry of the detailed level often creates errors when using neutral formats and due to the amount of data that is needed to describe all details it is very cumbersome to exchange information. If only the detail level that is needed for a FM is created, neutral formats will be sufficient for transfer of geometry. This technique together with the benefits and limitations it gives is described in reference 4.

5. Some Requirement on a Virtual Concept (VC) Solution

The Virtual Concept modelling, described below, explains how this simplified modelling can be done in a Virtual Reality system.

A Virtual Concept modeller, in a Virtual Reality system, must have simple tools for creation of simple solid geometry as well as the import functionality of CAD data and other information both direct and via support of stable neutral formats such as IGES/VDA-FS/SET or STEP. The solution must to be able to export geometry to CAD systems and in some cases import geometry. A modeller that directly creates and operates in STEP, instead of converting to/from STEP is a preferred solution due to the neutral nature of the database.

For complex assemblies, functionality to export structures comes with STEP, however most of today's CAD systems can not read or even handle structure information why this must be a function within the VC solution. A database-like tool to differentiate in-between different assemblies and identify differences, i.e. a component may have been changed or positioned different in the assembly, is also needed.

The other input sources that are needed are 3D digitisers for physical objects and in specific cases direct converters from CAD systems.

A simple cinematic package is also high on the requirement to be able to simulate motions as well as an interface to more functional dynamic packages for later verification from CAD data.

A mannequin would also facilitate ergonomic studies and assembly studies.

6. Next generation of possible solutions

With the possibilities of VR, the development process manufacturing companies have the potential of shortening the time-to-market considerably.

A company that wants to stay in the market needs to dramatically shorten lead-time at the same time as it maintains (or improves) quality together with a low production cost. This is sometimes refereed to as Time Monopoly.

The ability to deliver new solutions to the market in a shorter time than the competition, gives a tremendous competitive advantage since,

- the first products creates the market and thus sets the requirement on the solution
- the first products can have higher margin (no competitive price pressure)
- the first entrants to the market can set standards
- the first entrants takes the prestigious initial orders
- a late starter will still have their product obsolete at approximately the same time but the window of opportunity shrinks which impact profit dramatically.

Because of today's dependence on created CAD geometry, the often overworked models and the difficulties for an inexperienced user to work with CAD, the concept of Functional Modelling and Virtual Concept has been developed. Simple models can easily be created using limited tools within the Virtual Reality system. If the geometry fulfils the requirements of the Virtual Concept, the simple FM geometry is passed over for more detailed design in a CAD system. The environment gives more flexibility since most of the tedious transfer of geometry in-between the VR system and the CAD system can be avoided. A user can decide, depending on their preference and skill, if the geometry is created in a CAD system and imported, or if he prefers to create it within the VR system. Creation of the data within CAD requires that there is an interface from the VR system to the CAD system in order to propagate changes such as a part in an assembly has been mowed. The suggested process and phases is drafted in figure 4.

The environment should ideally also have other features and some of these are described later in this paper. After detail component design has been done in a CAD system, the detailed geometry should be transferred to the VR system for final verification before prototypes are built or production can start. Very often a physical prototype needs to be built due to legislation (i.e. for aero-engines) or subjective testing that can not be simulated. The more complex a design is and the larger an assembly is the more important computer aided tools will become. With very large assemblies, such as a submarine, there are no realistic alternatives to virtual reality tools.

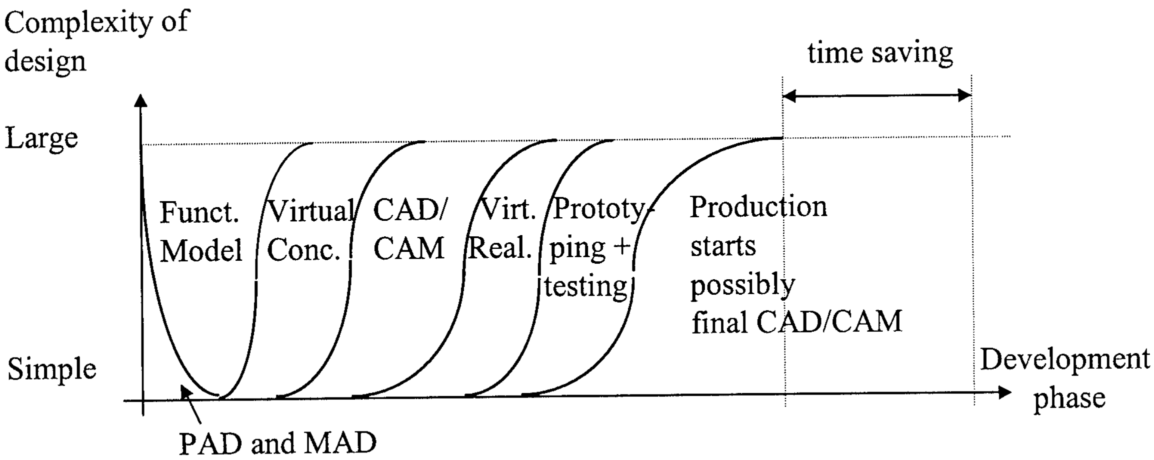

Figure 4*, a modified product development process using FM (Functional Modelling and Virtual Concept Modelling, ref. [5])*

Note: The y-axis, "complexity of design" refers to the either complex individual component or to the complexity of the end product in the sense of an assembly with a very large number of individual parts. For example a product like a submarine consists of more than 1 million individual components why all systems that attempt to use full amount of data, i.e. traditional CAD, will get severe performance problems. The only alternative is Virtual Concept Modelling with both simple Functional Modelling and a simplified representation of the geometry.

7. Conclusion

Traditional CAD systems do not meet requirement from the need to shorten lead time in development. Today's Virtual Reality tools have the promise to meet this need if they are combined with very simple and easy-to-use modelling- and mechanism tools. Preliminary studies shows a possibility to reduce development time a magnitude more than any implementation of existing CAD systems can provide. The technology for creating these solutions already exist but in order to implement them at different companies, a change in their product development process must take place.

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14. Abstract

Virtual Manufacturing (VM) is an integrated, synthetic manufacturing environment exercised to enhance all levels of decision and control. This process uses product, process and resource models to evaluate the producibility and affordability of new product concepts prior to commitment to the final product design. Design processes are captured in the single geometric database and integrated with the planned manufacturing processes resulting in a simulation of the manufacturing environment. The critical questions of manufacturing cycle time, people resource requirements and physical resource requirements for various scenarios are quantified with simulation.

Thus, Virtual Manufacturing (VM) is a tool to achieve more affordable aircraft designs and operate in new modes characterized by reduced design cycles and risk reducing techniques.

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